

SOUTHWEST FISHERIES CENTER ADMINISTRATIVE
REPORTS, 1978

No. 1H-16H

BEHAVIORAL RESPONSE OF YELLOWFIN TUNA, Thunnus albacares
AND KAWAKAWA, Euthynnus affinis, TO TURBIDITY

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January 1978

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Note: This study was supported by funds provided by the Deep Ocean Mining Environmental Study (DOMES) program.



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As a part of the Deep Ocean Mining Environmental Study (DOMES), the following studies were designed to investigate the effects of the surface discharge of bottom sediments on tuna behavior. Tuna schools may react to the increased turbidity caused by the suspended sediments. My study examines the behavioral responses of captive tuna to varying turbidity levels. Other non-behavioral investigations should be necessary only if behavioral data indicate that tuna will spend significant amounts of time in turbid areas. In the following experiments, I assumed that, depending upon motivational and environmental factors, there exists a level of turbidity that tuna will avoid.

Pairs of or single yellowfin tuna, Thunnus albacares, and kawakawa Euthynnus affinis, were held in outdoor 7.3 m diameter by 1.2 m deep tanks. The tanks were supplied with a continuous flow of low turbidity seawater in the range of 0.6 to 1.0 Nephelometric Turbidity Units (NTU). Tuna were fed frozen smelt at a rate of approximately 10% of body weight per day. Details of catching, transporting, and maintaining live tuna in captivity are available elsewhere.¹

¹Nakamura, E. L., 1972. Development and uses of facilities for studying tuna behavior. In H. E. Winn and B. L. Olla (editors), Behavior of marine animals. Current perspectives in research 2: Vertebrates, p. 245-277. Plenum Publishing Corporation.

A trial consisted of a 6-min control observation period (which sometimes included a 1-min control feeding period) followed by the introduction of the suspended material into the tank, and a 6- to 15-min observation period of the responses of the tuna to the resulting cloud. The observation period ended when the cloud dispersed, or when the tuna consistently ignored the cloud.

The water depth in the tank was lowered to 0.5 m for kawakawa and about 0.6 m for yellowfin tuna prior to a trial (in the first study on the single large yellowfin tuna, water depth was maintained at 1.2 m). The lowered water level minimized vertical variations of turbidity within the cloud. The inflow of seawater was shut off at the beginning of each trial to reduce the cloud dispersion rate. Trials were done between 1030 and 1530 h, either once or twice per day, and usually on alternate days.

Preliminary trials were monitored visually by a hidden observer in a tower overlooking the tank. Later trials were monitored with a videotape system mounted on the roof of the tower, and supplemented by an audio record made by the observer. Periodically, water samples were taken from the cloud and other areas of the tank by a second experimenter. If feeding was included in the trial, the second observer also threw food into various areas of the tank. This experimenter and sampling were, of necessity, plainly visible to the tuna. The suspended material was deep sea mud from DOMES site C. The mud was weighed, mixed with seawater in a blender, diluted to 3.8 liters, and poured into the tank from a bucket. Sample turbidities

were measured with a nephelometric turbidimeter.² A series of dilutions of a suspension of DOMES mud was analyzed to determine the relationship between turbidity and concentration of suspended sediments. Dry weights of suspended sediments were determined by total residue.³ There is a linear relationship between the measured turbidity in NTU's and sediment concentration in milligrams per liter of DOMES site C mud. One NTU corresponds to about 1.4 mg/liter of DOMES mud.

Trials without videotape documentation consisted of eight turbid trials and two control trials (plain seawater) with a pair of kawakawa, and seven turbid and two control trials on a single large yellowfin tuna. Most of these trials included feeding--the tuna were fed in and out of clouds to determine how feeding motivation affects avoidance. Videotape documented trials included 15 turbid and 2 control trials on a pair of kawakawa, and 16 turbid and 2 control trials on a pair of yellowfin tuna. These trials were designed to determine avoidance reactions independent of feeding motivation. In six final trials the yellowfin tuna pair were fed, but only in the turbid clouds.

OBSERVATIONS

Turbidity clouds were often very irregular in shape; each was different due to the wind speed and direction, water current, activity of the tuna, and amount of material added. The cloud circled the tank

²H.F. Industries model DRT-1000 calibrated against Formazin solutions.

³Total residue dried at 103°-105°C; American Public Health Association, 1975. Standard methods for the examination of water and waste water including bottom sediments and sludges. 14th edition. A.P.H.A., New York.

1 to 2 times per trial. Thus cloud position could not be predicted by the tuna or avoided by using one specific swimming pattern. Early trials with both species of tuna usually resulted in some initial probing or passing through clouds at high turbidities. After a few of these passes, and after a few trials, tuna would often turn away from the cloud at a distance; however, avoidance responses while in cloud peripheries or centers were also observed.

The results of the non-videotaped trials are summarized in Tables 1 and 2. The kawakawa pair behaved and were treated as a unit. The behavioral categories are based primarily on the physical position of the tuna with respect to the cloud. The "avoid" categories show the lowest measured turbidity levels which were avoided; and the "pass through" category represents the highest turbidity through which the tuna regularly swam. At turbidity levels in the "pass/not eat" category, the tuna usually entered the cloud to reach food, but did not eat the food. Abnormal behavior indicative of stress was observed frequently, especially in the early kawakawa trials. Both kawakawa and yellowfin tuna would eat in the clouds, although they were fed both in and out of the clouds. However, in one trial when fed live anchovies (rather than dead smelt); the kawakawa passed through higher turbidities (4.0 NTU) than before. Otherwise, feeding motivation did not result in a greater willingness to enter turbid areas. Kawakawa generally passed through higher turbidities than the yellowfin tuna. In one instance, the yellowfin tuna refused to eat in a 1.2 NTU cloud relative to 0.85 NTU surroundings.

The results of the videotaped trials are recorded in Tables 3 and 4. "Avoid-1" is the turbidity at which complete physical avoidance occurred; "Avoid-2," the level at which the tuna avoided the cloud more often than they passed through; "Avoid-3," the level at which pass throughs occurred more frequently than avoidance; and "Pass through," the level which the tuna passed through the cloud in virtually all cases. At turbidity levels in the last category, the tuna were often reacting behaviorally to the cloud (speed changes, turns, fin movements, etc.), but in all cases were passing through. The recorded turbidity levels avoided were not necessarily the absolute minimum levels actually avoided, because often samples were not taken on the last avoidance before a pass through. However, turbidity levels at which the tuna passed through represent true maxima, as samples were always taken immediately after a pass through.

In all but a few trials with the kawakawa, the pair of tuna were treated as a unit. Generally one tuna followed and reacted exactly like the leader. However, in three kawakawa trials, one of the pair of videotaped individuals was tested with a new but sick tuna. The sick fish was less efficient at avoiding (discriminating) the clouds; and thus, the two tuna were examined individually. In a final trial the healthy kawakawa was tested alone.

In the yellowfin, but not the kawakawa, the initial amount of sediment introduced (10 versus 25 or 50 g) correlated with the turbidity levels avoided and tolerated. This correlation is related to the larger size of the clouds which were formed from greater amounts of

sediments. For example, in a 25 g trial, the turbidity dropped to a level of 3.0 NTU when the cloud covered a much larger area than a 3.0 NTU, 10 g cloud. The yellowfin tuna avoided larger clouds with less frequency than smaller clouds with similar turbidities. Perhaps the relatively large yellowfin tuna (3,121 and 3,517 g in weight, versus about 1,500 g for the kawakawa) were less agile in avoiding a large cloud within the confines of the tank.

The yellowfin tuna consistently avoided the 10 g clouds until the turbidity dropped to 1.6-2.2 NTU, whereas kawakawa tolerated turbidities up to 4.4 NTU. In a few feeding trials, the yellowfin tuna entered turbidities up to 7.4 NTU in order to feed. In these trials food was thrown exclusively into the clouds. Unlike all other trials, the turbidity levels tolerated in these feeding trials increased over the period of testing (5 days). This appears to be a learning phenomena; it is likely that tuna could be trained to enter extremely high turbidities to feed.

CONCLUSIONS

From the data it is clear that tuna can avoid areas of suspended site C sediment. Kawakawa were more tolerant of high turbidities than were yellowfin tuna. This can possibly be explained by the more coastal distribution of kawakawa, and the almost exclusively open sea distribution of yellowfin tuna. Based upon their ecology, skipjack tuna, Katsuwonus pelamis, will most likely show avoidance behavior similar to yellowfin tuna.

Occasionally avoidance reactions to the higher turbidities were extremely abrupt. Yet, the clouds did not seem exceedingly aversive or toxic since the tuna usually did not get extremely upset or ill as a result of short-term exposure to turbidities in the range tested. At sufficiently low turbidities the tuna would even feed in the clouds (up to 7.4 NTU). Of course the high turbidities were encountered only in the form of a cloud which left a large portion of the tank relatively clear. Preliminary experiments indicated that in turbidities filling the entire tank (2-3 NTU), the tuna often became sufficiently upset to cease feeding. It often appeared that in addition to initial probing of the clouds, the tuna were attracted to cloud regions at low turbidities in the non-feeding trials. However, the present experiments were not designed to measure such an effect; and the attraction could represent mere curiosity. Captive tuna may tolerate higher turbidity levels than they would in the open ocean. All experimental animals were regularly exposed to high turbidities due to tank cleaning. In addition, the two yellowfin tuna observed in the videotaped trials had been exposed to more than 2 weeks of turbid water (approximately 1.5 NTU) when our water system broke down. Although oceanic tuna may find low levels of turbidity aversive, they may be inefficient at avoiding low levels due to an inability to detect the gradual gradients within the clouds. (An ongoing study is attempting to determine thresholds for turbidity detection.) However, the avoidance responses seen in captivity appeared to be visually mediated; and tuna have acute visual capabilities. Thus, tuna should be able to

detect gradual gradients of turbidity. The actual response in the ocean will depend on the absolute level and gradients of turbidity encountered, on critical levels of turbidity for the species in question, and on the motivational state of the tuna.

Table 1.--Non-videotaped kawakawa trials.

DOMES mud added (g)	Avoid-not eat (NTU)	Pass-not eat (NTU)	Pass and eat (NTU)
25			3.5
50	4.45	2.2	1.3
50	6.0		3.2
100	2.9	2.1	0.88
200	4.5		2.85
¹ 200	6.9	4.0	
200	3.2	2.9	
² 300			2.5

¹Live bait used; it was difficult to determine where it was eaten but feeding did occur.

²In this case cloud dispersed over entire tank. Tuna willing to feed, but not avidly.

Table 2.--Non-videotaped yellowfin tuna trials.

DOMES mud added (g)	Avoid-not eat (NTU) ¹	Pass-not eat (NTU)	Pass and eat (NTU)
25	7.0	1.2, 1.5	.85
100	2.15	2.1	.97
100		2.1, 1.5	2.1
100	2.9		2.6
150	3.4		2.3
² 300	2.1 / 1.6	2.2	2.2
400	2.75 / 2.0		1.9

¹If two values x/y are given, x is the turbidity of the cloud and y is the turbidity in the less turbid part of the tank, if different from normal ambient (.6-1.1 NTU).

²No food was introduced during this trial.

Table 3.--Videotaped kawakawa trials.

DOMES mud added (g)	Avoid-1 (NTU)	Avoid-2 (NTU)	Avoid-3 (NTU)	Pass through	Maximum turbidity measured ¹	
					(NTU)	Time (sec)
10	10.2	3.7	4.1, 5.2	2.4	10.0	35
25	3.0, 5.2		3.4	2.9	15.5	30
25		6.1		2.83	6.1	95
25	12.0			4.1	12.0	50
50	32.0	4.4	3.8	2.05	32.0	55
50	25.0			3.5	25.0	37
50	18.0	5.9	3.9	1.9	18.0	60
50	3.3			2.7	14.5	180
100	8.8	5.6		3.3	36.0	55
100	4.3	5.4		3.3	58.0	38
100	4.8	4.3, 3.5		4.43	42.0	70
² 25A	3.3			2.9	10.0	55
25B			10.0	3.3	10.0	55
50A	4.9	6.9	3.3	3.3	23.0	63
50B	4.9	7.5	6.9	3.3	23.0	63
100A	3.9			4.5	32.0	45
100B	32.0			23.0	32.0	45
³ 50A	3.2	2.5	2.4	2.3	11.0	45

¹Maximum turbidity measured and time after the addition of mud when the measurement was taken.

²Tuna in subsequently listed runs treated separately due to differences in their responses. "A" was healthy and feeding; "B" was sick, not feeding, and died soon after.

³Last trial was done with tuna "A" alone in the tank.

Avoid-1 - Complete avoidance of cloud.
 Avoid-2 - Avoided more than passed through.
 Avoid-3 - Passed through more than avoided.
 Pass through - Consistently passed through turbidity cloud.

Table 4.--Videotaped yellowfin tuna trials.

DOMES mud added (g)	Avoid-1 (NTU)	Avoid-2 (NTU)	Avoid-3 (NTU)	Pass through (NTU)	Feed (NTU)	Maximum turbidity measured ¹	
						(NTU)	Time (sec)
Non-feeding trials							
10	3.2			1.6		6.7	22
10	2.9		1.9	1.7		5.9	26
10	2.9			2.2		7.0	33
10	2.9	1.5		1.9		5.9	20
10	2.6		2.3	1.9		6.1	27
10	2.8		2.1	1.6		14.0	25
10	2.2			2.1		6.5	22
25	3.1			2.7		11.5	39
25	2.9			3.0		9.8	25
25	2.8			2.1		6.6	30
25	3.6		2.8	2.7		16.2	21
25	2.9	3.9	2.05	2.7		18.0	35
25	6.0		3.9	2.85		8.6	35
25	11.7		5.3	3.0		14.0	32
50	3.3			2.6		28.0	32
50	19.0	4.2		2.9		19.0	34
Feeding trials (in chronological order)							
50	8.2		4.4	3.9	3.9	30.0	25
25	16.5		5.0	3.2	² 5.5	16.5	40
25	10.5		14.5	6.9	6.3	14.5	33
50			14.5	6.0	6.0	14.5	54
50	28.5			8.2	7.3	28.5	44
25		9.6		7.4	7.4	9.6	52

¹Maximum turbidity measured and time after the addition of mud when the measurement was taken.

²Cloud was avoided except for feeding.

Avoid-1	- Complete avoidance of cloud.
Avoid-2	- Avoided more than passed through.
Avoid-3	- Passed through more than avoided.
Pass through	- Consistently passed through cloud.
Feed	- Passed through and fed in cloud.

INCREASING COMPUTATIONAL EFFICIENCY FOR SEMI-SEPARABLE
MARKOV DECISION PROCESSES

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January 1978
1st revision February 1978
2d revision March 1978

DRAFT FOR COMMENT

I. Introduction

One of the major deterrents to using Markov decision processes (MDP) in real applications is the extremely large problem size that may arise. Several authors (Koehler, Whinston, and Wright [4]; Puterman [5]; and references cited by these papers) have attacked this problem by developing more efficient solution algorithms for a general MDP. In this paper, the more standard linear programming (LP) approach is used. For a wide class of MDP's that arise in real applications, the resulting LP can be greatly reduced in dimensionality. This allows for efficient aggregation of the LP into smaller, easily solved problems, as well as easily derived qualitative properties of solutions.

The class of problems considered is similar to the separable programs considered by Denardo [1]. However, the method of proof is entirely different. This allows for the relaxation of the assumption that the one period return function be separable. The final rows of the reduced LP can be interpreted in terms of the distribution function of leaving each state; this fact, and the readily obtained qualitative properties of a solution can often lead to even greater reduction in problem size.

II. The Model and Main Results

Problems that arise in the context of capital accumulation and consumption, managing renewable resources, reservoir management, and inventory control and production, involve solving the following mathematical program:

$$f(x) = \text{maximum } \{G(x, y) + \alpha E f(s[y, D]) : y \in Y(x)\} \quad (2.1)$$

$$x \in X$$

where X is the set of states, $Y(x)$ is the set of feasible decisions for each $x \in X$, and D is a random variable. These are called "semi-separable" problems (c.f., Denardo [1]) since the transition function depends only on the decision, not on the state.

It is well known (see d'Epenoux [2]) that an optimal policy to the discrete problem, if one exists, is a solution to the following LP:

$$\min \sum_{x \in X} f_x \quad (2.2)$$

subject to $\sum_{j \in X} (\delta_{xj} - \alpha p_j^y) f_j \geq G(x, y) \quad y \in Y(x), x \in X$

$$\text{where } \delta_{xj} = \begin{cases} 0 & \text{if } x \neq j \\ 1 & \text{if } x = j \end{cases}$$

and p_j^y is the discrete probability of going to state j given decision j . p_j^y can be obtained by discretizing $s[y, D]$. Fox [3] gives a discussion of methods of discretizing a continuous problem. Note also that the usual problem has p_{xj}^y . However, by the semi-separable assumption, $p_{xj}^y = p_j^y$.

The equivalent dual problem is:

$$\begin{aligned} \max \quad & \sum_{x \in X} \sum_{y \in Y(x)} G_x^y v_x^y \\ \text{subject to:} \quad & \sum_{x \in X} \sum_{y \in Y(x)} (\delta_{xj} - \alpha P_j^y) v_x^y = 1 \quad , \quad j \in X \end{aligned} \quad (2.3)$$

$$v_x^y \geq 0 \quad \text{for all } y \in Y(x); x \in X$$

where G_x^y is the discrete equivalent of $G(x, y)$.

In this section, attention is restricted to x, y scalar. Section III shows that this is without loss of generality. $Y(x)$ is assumed to be of the form:

$$Y(x) = \{y : 0 \leq y \leq x\} . \quad (2.4)$$

The cardinality of X , $|X|$, is assumed to be $n+1$.

Theorem 2.1 shows that semi-separable MDP's have the property that it is possible a priori to reduce the MDP to a MDP that has two actions per state.

Theorem 2.1 For each j , $0 \leq j \leq n$, let $b_j^* = \text{maximum}_{0 \leq i \leq j} \{G_j^i - G_{j-1}^i\}$, and let i_j^* be defined as the i where b_j^* obtains its maximum. Let $A(j)$ be an optimal policy function. Then:

$$\begin{aligned} \text{either } A(j) &= j \\ \text{or } A(j) &= i_j^* \end{aligned}$$

Proof: Consider the dual LP (2.3). Since the rows are equalities, add rows 1 through n to row 0 (row 0 is the first row constraint, row n the last row constraint), rows 2 through n to row 1, etc., yielding a new LP:

$$\text{maximize } \sum_{x=0}^n \sum_{i=0}^x G_x^i v_x^i \quad (2.5)$$

$$\text{s.t. } \sum_{i=0}^n \sum_{x=i}^n \left\{ \delta_{x \geq j} - \alpha \sum_{k=j}^n P_k^i \right\} v_x^i = n+1-j \quad j = 0, 1, \dots, n$$

$$v_x^i \geq 0 \quad x = 0, \dots, n$$

$$i = 0, 1, \dots, x$$

where $\delta_{x \geq j} = \begin{cases} 0 & x < j \\ 1 & x \geq j \end{cases}$

Transform variables as follows: for each i, i = 0, 1, ..., n

$$w_n^i = v_n^i \quad (2.6)$$

$$w_j^i - w_{j+1}^i = v_j^i \quad j = i, i+1, \dots, n$$

or equivalently:

$$w_n^i = v_n^i$$

$$w_{n-1}^i = v_n^i + v_{n-1}^i$$

$$\vdots$$

$$w_i^i = v_n^i + v_{n-1}^i + \dots + v_i^i \quad (2.7)$$

The LP now becomes:

$$\begin{aligned}
& \text{maximize} \quad \sum_{x=0}^n \sum_{i=0}^{x-1} \left(G_x^i - G_{x-1}^i \right) w_x^i + \sum_{x=0}^n G_x^x w_x^x \\
& \text{s.t.} \quad \sum_{i=0}^n \left\{ \delta_{x \geq j} - \alpha \sum_{k=j}^n P_k^i \right\} w_i^i + \sum_{\substack{i=0 \\ i \neq j}}^j w_j^i = n+1-j \quad j = 0, 1, \dots, n \\
& \quad w_n^j \geq 0 \quad j = 0, 1, \dots, n \\
& \quad w_j^i - w_{j+1}^i \geq 0 \quad j = 0, 1, \dots, n-1, i = 0, 1, \dots, j
\end{aligned} \tag{2.8}$$

For an arbitrary j , $1 \leq j \leq n$, and for some i , $0 \leq i_j < j$,

$i_j \neq i_j^*$, transform variables by:

$$\begin{aligned}
\bar{w}_j^i &= w_j^i \\
\bar{w}_j^{i_j^*} &= w_j^{i_j} + w_j^{i_j^*}
\end{aligned}$$

or equivalently:

$$\begin{aligned}
\bar{w}_j^i &= w_j^i \\
\bar{w}_j^{i_j^*} - \bar{w}_j^{i_j} &= w_j^{i_j^*}
\end{aligned} \tag{2.9}$$

Then the LP (2.8) becomes:

$$\begin{aligned}
& \text{maximize} \quad \sum_{x=0}^n \sum_{\substack{i=0 \\ i \neq i_x^* \\ i \neq i_j}}^{x-1} \left(G_x^i - G_{x-1}^i \right) w_x^i + \sum_{x=0}^n G_x^x w_x^x \\
& \quad + \sum_{\substack{x=1 \\ x \neq j}}^n \left(G_x^{i_x^*} - G_{x-1}^{i_x^*} \right) w_x^{i_x^*} + \left(G_j^{i_j} - G_{j-1}^{i_j} \right) \bar{w}_j^{i_j} + \left(\left(G_j^{i_j} - G_{j-1}^{i_j} \right) - \left(G_j^{i_j^*} - G_{j-1}^{i_j^*} \right) \right) \bar{w}_j^{i_j^*}
\end{aligned}$$

$$\text{s.t.} \quad \sum_{i=0}^n \left\{ \delta_{x \geq y} - \alpha \sum_{k=y}^n P_k^i \right\} w_i^i + \sum_{i=0}^n w_y^i = n+1-y \quad \begin{array}{l} y = 0, 1, \dots, n \\ y \neq j \end{array}$$

(2.10a)

$$\sum_{i=0}^n \left\{ \delta_{x \geq j} - \alpha \sum_{k=j}^n P_k^i \right\} w_i^i + \sum_{i=0}^n w_j^i + \bar{w}_j^{i_j^*} = n+1-j$$

$$\begin{array}{l} i = i_j^* \\ i = i_j \end{array}$$

$$w_n^i \geq 0 \quad i = 0, 1, \dots, n$$

$$w_y^i - w_{y+1}^i \geq 0 \quad \begin{array}{l} y = 0, 1, \dots, n-1; \\ i = 0, 1, \dots, y \end{array}$$

(2.10b)

$$w_{j-1}^{i_j} - \bar{w}_j^{i_j} \geq 0$$

$$w_{j-1}^{i_j^*} - \bar{w}_j^{i_j^*} \geq -\bar{w}_j^{i_j}$$

$$\bar{w}_j^{i_j} - w_{j+1}^{i_j} \geq 0$$

$$\bar{w}_j^{i_j^*} - w_{j+1}^{i_j^*} \geq \bar{w}_j^{i_j}$$

$$w_j^{i_j^*} - \bar{w}_j^{i_j} \geq 0$$

Examine the constraints involving $\bar{w}_j^i$:

$$\bar{w}_j^i \geq \bar{w}_j^{i*} - w_{j-1}^{i*}$$

$$\bar{w}_j^i \geq w_{j+1}^i$$

$$\bar{w}_j^{i*} \geq \bar{w}_j^i$$

$$w_{j-1}^i \geq \bar{w}_j^i$$

$$\bar{w}_j^{i*} - w_{j+1}^{i*} \geq \bar{w}_j^i$$

Since $\bar{w}_j^i$ only appears in the constraints (2.10b), and has a nonpositive objective function coefficient, at an optimal solution it will have a value at a lower bound, which is the greater of w_{j+1}^i , $w_j^{i*} - w_{j-1}^{i*}$.

If $\bar{w}_j^i = w_{j+1}^i$, then from (2.7) and (2.9), $v_j^i \equiv 0$.

If $\bar{w}_j^{i*} - w_{j-1}^{i*} > w_{j+1}^i$, then from (2.) $w_j^i = \left(\bar{w}_j^{i*} - w_{j-1}^{i*} \right) - w_{j-1}^{i*}$

which implies:

$$2w_j^i = w_j^{i*} - w_{j-1}^{i*}$$

From (2.8),

$$0 \geq w_j^{i*} - w_{j-1}^{i*} = 2w_j^i \geq 0$$

so that $w_j^{i_j} \equiv 0$. Since $w_j^{i_j} \geq w_{j+1}^{i_j}$, then $w_j^{i_j} = w_{j+1}^{i_j} = 0$, which implies $v_j^{i_j} \equiv 0$. Since j and i_j were chosen arbitrarily, the proof holds for each j and i_j .

□

The transformations in theorem 2.1 are only necessary to prove that an optimal policy chooses either x or i_x^* . Corollary 2.1 gives the reduced LP.

Corollary 2.1 In (2.2), let i_j^* be defined as in theorem 2.1. Then, an optimal solution to:

$$\begin{aligned}
 & \text{minimize } \sum_{x=0}^n f_x \\
 & \text{s.t. } \sum_{x=0}^n \left(\delta_{ix} - \alpha P_x^i \right) f_x \geq G_1^i \quad i = 0, 1, \dots, n \\
 & \sum_{x=0}^n \left(\delta_{i_j^* x} - \alpha P_x^{i_j^*} \right) f_x \geq G_j^{i_j^*} \quad j = 0, 1, \dots, n
 \end{aligned} \tag{2.11}$$

is also an optimal solution to (2.2).

Proof: Immediate consequence of theorem 2.1.

□

An alternate form to (2.11), which is sparser when computations are done is:

$$\begin{aligned}
& \text{minimize } \sum_{x=0}^n f_x \\
& \text{s.t. } \sum_{x=0}^n \left(\delta_{ix} - \alpha P_x^i \right) f_x - \lambda_i^i = G_i^i \quad i = 0, 1, \dots, n \\
& \qquad \qquad \qquad f_j - f_{i_j^*} + \lambda_{i_j^*}^{i_j^*} - \lambda_j^{i_j^*} = G_j^{i_j^*} \quad j = 0, 1, \dots, n \\
& \qquad \qquad \qquad \lambda_i^i, \lambda_j^{i_j^*} \geq 0 \quad i = 0, 1, \dots, n \\
& \qquad \qquad \qquad \qquad \qquad \qquad j = 0, 1, \dots, n
\end{aligned} \tag{2.12}$$

which is derived by making the constraints in (2.11) equalities, and then subtracting the appropriate rows.

For certain special cases, the results of theorem 2.1 can be made stronger, and derived more directly. This is especially true of separable MDP's (Denardo [1]). Let $G(x, y) = a(x) + b(y)$.

Transform variables by:

$$\begin{aligned}
f_0 &= u_0 \\
f_i &= \sum_{j=0}^n u_i \quad i = 1, \dots, n
\end{aligned}$$

or equivalently:

$$u_i = f_i - f_{i-1} \quad i = 0, 1, \dots, n$$

It is straightforward to show that at an optimal solution:

$$f_i^* \geq \left(a(i) - a(i-1) \right) + f_{i-1}^* \tag{2.13}$$

when equation (2.13) is valid, all the rows equivalent to choosing j as the action are redundant with:

$$\sum_{x=0}^n \left(\delta_{xy} - \alpha p_x^j \right) f_x \geq a(j) + b(j)$$

$$f_{j+1} - f_{j+i-1} \geq a(j+i) - a(j+i-1)$$

$$i = 1, 2, \dots, n-j$$

This leads to a reduced LP:

$$\begin{aligned} & \text{minimize} \quad \sum_{x=0}^n (n+1-x) u_x \\ & \text{s.t.} \quad \sum_{x=0}^n \left(\delta_{x \leq j} - \alpha \sum_{i=x}^n p_i^j \right) u_x \geq a(j) + b(j) \quad j = 0, 1, \dots, n \\ & \quad \quad \quad u_x \geq a(x) - a(x-1) \quad x = 1, 2, \dots, n \end{aligned} \tag{2.14}$$

where $\delta_{x \leq j}$ denotes:

$$\delta_{x \leq j} = \begin{cases} 1 & x \leq j \\ 0 & x > j \end{cases}$$

The LP in (2.14) can be solved with a $(n+1 \times n+1)$ constraint matrix. The equivalent formulation in Denardo (1968) has a $(2n+2 \times n+1)$ constraint matrix.

III. Extensions and Discussion

The proof of theorem 2.1 does not depend on x, y being scalars. It only depends on the semi-separable assumption, and the assumption the $Y(x) = \{y : 0 \leq y \leq x\}$. The vector case is proven in a similar manner. The dual variables are again grouped by choosing action y from all states $x \geq y$, and then making the same transformations of variables.

The LP (2.11) can be solved using linear programming, or else can be solved using successive approximations or similar iterative techniques (see Koehler et al. [4]; Puterman [5]) with a reduced action space. The reduced LP can also be used to prove qualitative results about optimal policies when further assumptions are made on the form of $G(\cdot, \cdot)$. This will be explored more fully in a future paper.

Even with the reduction in problem size between (2.11) and (2.2), for many real applications any useful discrete state space will still bring about an exceedingly large LP. However, the reduced LP gives more insight into how to effectively aggregate rows or columns in order to further reduce the size of the LP, using results similar to those in Zipkin [6].

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QUALITATIVE PROPERTIES OF OPTIMAL POLICIES FOR
SEMI-SEPARABLE MARKOV DECISION PROCESSES

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February 1978
1st revision March 1978
2d revision April 1978

DRAFT FOR COMMENT

I. Introduction

A previous paper (Mendelssohn [4]) shows how to reduce the computational effort involved in solving "semi-separable" Markov decision processes (MDP's). Semi-separable MDP's often arise as discrete approximations to the problem of finding $f(x)$ such that:

$$f(x) = \max \left\{ G(x, y) + \alpha E \left(f(s[y, D]) \right) : y \in Y(x); x \in X \right\}$$
$$0 \leq \alpha < 1 \quad (1)$$

Problems of this form arise in the context of harvesting problems, capital accumulation and consumption, reservoir management, and other areas of stochastic optimization. The main characteristic is that the transition probabilities depend only on the decision y , and not on the state x . As such, semi-separable processes are an extension of the "separable" MDP's discussed by Denardo [2], where it is further assumed that $G(x, y) = a(x) + b(y)$.

If it is assumed that $Y(x) = \{y : 0 \leq y \leq x\}$, Mendelssohn [4] shows that only two decisions can be optimal at any state x . Let $A(x)$ be an optimal policy function. Let G_x^y ($x = 0, 1, \dots, n$; $y = 0, 1, \dots, x$), be a discretization of $G(x, y)$. Define b_j^* as:

$$b_j^* = \max_{0 \leq i \leq j} \left(G_j^i - G_{j-1}^i \right) \quad j = 1, 2, \dots, n$$

and let i_j^* be the argument where b_j^* obtains its maximum. Then [4]:

$$A(x) = x \text{ or } i_x^*, \quad x = 0, 1, \dots, n. \quad (2)$$

An interesting feature of (2) is that strong qualitative properties of an optimal policy depend only on properties of the one-period return function, and not on the transition probabilities. This makes it possible to generalize results in specific contexts that have not proven amenable to other forms of analysis.

II. Qualitative Results

A model of interest in capital accumulation, economic growth and managing renewable resources (see Brock and Mirman [1], Mirman and Zilcha [6], Mendelssohn and Sobel [5], and references cited in these papers) assumes that:

(i) $G(x, y) = G(x-y)$; $G(\cdot)$ concave, nondecreasing and continuous

(ii) $s[\cdot, D]$ concave and continuous.

Usually it is also assumed that $s[\cdot, D]$ is nondecreasing. It is then shown that for a continuous state model:

$$0 \leq \frac{d}{dx} A(x) \leq 1 \quad (3)$$

or for a discrete state model:

$$A(x+1) = \text{either } A(x) \text{ or } A(x) + 1. \quad (4)$$

Theorem 2.1 generalizes these results by only requiring that $G(\cdot)$ be concave, and no assumptions on $s[\cdot, \cdot]$. The result is for the discrete state space model.

Theorem 2.1 In the discrete version of (1), assume
 $G(x, y) = G(x-y)$, $G(\cdot)$ concave and not separable. Then there exist
j numbers:

$$0 \leq x_1 \leq x_2 \leq x_3 \dots \leq x_j \leq n$$

such that:

$$A(x) = \begin{cases} x & 0 \leq x \leq x_1 \\ x-1 & x_i < x \leq x_{i+1}; \quad i \text{ odd} \\ x & x_i < x \leq x_{i+1}; \quad i \text{ even} \end{cases}$$

$$i = 0, 1, \dots, j$$

Proof. $G(\cdot)$ is assumed to be concave. This implies $i_j^* = j-1$, so
 that $b_j^* = b^* = G(1) - G(0)$. The result is then straightforward. □

If $G(x-y) = p \cdot (x-y)$, then i_x^* could be any $y < x$. However,
 the separable form of $p \cdot (x-y)$ provides a straightforward modification
 to theorem 2.1.

Corollary 2.1 If under the conditions of theorem 2.1,
 $G(x-y) = p \cdot (x-y)$, then there exist j integers:

$$0 \leq x_1 \leq x_2 \leq x_3 \leq \dots \leq x_j \leq n$$

such that

$$\begin{cases} x & 0 \leq x < x_1 \\ x_i & x_i \leq x < x_{i+1} & i \text{ odd} \\ x & x_i \leq x < x_{i+1} & i \text{ even} \end{cases}$$

In corollary 2.1, the x_i , i odd, are the discrete equivalent of local maxima of:

$$\alpha p E \left\{ f(s[y, D]) \right\} - p \cdot y$$

and the x_i 's, i even are the smallest points on the interval (x_i, x_{i+2}) , i odd, such that:

$$\left[\alpha p E \left\{ f(s[x_{i+2}, D]) \right\} - p \cdot x_{i+2} \right] - \left[\alpha p E \left\{ f(s[x_i, D]) \right\} - p x_i \right] > 0$$

and

$$\left[\alpha p E \left\{ f(s[x_{i+1}, D]) \right\} - p \cdot x_{i+1} \right] - \left[\alpha p E \left\{ f(s[x_i, D]) \right\} - p x_i \right] > 0$$

III. Computational Results

For some problems, it is known a priori that if $A(x) \neq x$, then $A(x+1) \neq x+1$. In the context of theorem 2.1, this is true if it is assumed that $s[\cdot, D]$ is concave (Mendelssohn and Sobel [5]). It may also be known, say from the two-period approximation to the infinite horizon problem, that:

$$A(x) = \begin{cases} x & \text{for } x \leq j \\ x-1 & \text{for } x \geq j^u \end{cases} \quad (5)$$

The linear program that solves this problem is:

$$\text{minimize } \sum_{x=0}^n f_x \quad (6)$$

$$\text{s.t. } \sum_{x=0}^n \left(\delta_{xj} - \alpha P_x^j \right) f_x \geq G(0) \quad j = 0, 1, \dots, n \quad (6a)$$

$$\sum_{x=0}^n \left(\delta_{x, j-1} - \alpha P_x^{j-1} \right) f_x \geq G(1) \quad j = 0, 1, \dots, n \quad (6b)$$

$$\text{where } \delta_{x,j} = \begin{cases} 0 & x \neq j \\ 1 & x = j \end{cases}$$

From (5), it follows that equality must hold in (6a) for $0 \leq j \leq j^L$, and equality must hold in (6b) for $j^u \leq j \leq n$. These variables can be solved for in terms of $f_{j^L}, f_{j^L+1}, \dots, f_{j^u-1}$, so

that the remaining LP can be greatly reduced in size. The new LP can also be solved by iterative methods such as successive approximations with greatly reduced computational effort.

It should be noted, however, that even if j^L, j^u are not known a priori, a sparse representation of (6) is possible. Transform variables by:

$$f_i = \sum_{j=0}^i v_j \quad i = 0, 1, \dots, n$$

and transform (6) into equality constraints by subtracting surplus variables. This yields:

$$\text{minimize } \sum_{x=0}^n (n+1-x)v_x \quad (7)$$

$$\text{s.t. } \sum_{x=0}^n \left(\delta_{x \leq j} - \alpha \sum_{i=x}^n p_i^j \right) v_j - \lambda_j^j = G(0) \quad j = 0, 1, \dots, n \quad (7a)$$

$$v_{j+1} + \lambda_j^j - \lambda_{j+1}^j = G(1) \quad j = 0, 1, \dots, n-1 \quad (7b)$$

$$\lambda_j^i \geq 0 \quad j = 0, 1, \dots, n \\ i = j, j-1$$

$$\text{where } \delta_{x \leq j} = \begin{cases} 1 & x \leq j \\ 0 & x > j \end{cases}$$

Besides being a much sparser LP, (7) has several other advantages over (6). The expectation of a nonnegative random variable x with distribution function $F(x)$ can be expressed as:

$$E(x) = \int_0^n [1 - F(x)] dx$$

(Karlin and Taylor [3]), where $P\{x \leq n\} = 1$. Note that the rows (7a) are the discrete equivalent of:

$$\int_0^n \left(\delta_{x \leq j} - \alpha \int_x^n s[j, \xi] dF(\xi) \right) v(x) dx \quad (8)$$

After choosing a grid to discretize (1), there are several ways of discretizing the transition probabilities. The LP (7) suggests that for this problem an efficient method may be to set:

$$\delta_{x \leq j} - \alpha \sum_{i=x}^n p_i^j = \delta_{x \leq j} - \alpha \int_x^n s[j, \xi] dF(\xi) \quad (9)$$

As integration tends to "smooth out" functions, (9) should give a better approximation than by using (6) and letting

$$p_{\mathbf{x}}^j = \int_{\mathbf{x}}^{\mathbf{x}+1} s[j, \xi] dF(\xi)$$

or some other approximation to the transition probabilities themselves.

III. Summary

In this paper, it has been assumed that $\mathbf{x}$, $\mathbf{y}$ are scalars. However, as pointed out in [4], similar results can be derived for $\mathbf{x}$, $\mathbf{y}$ vectors. Thus, related qualitative and computational results can be derived for the vector case. As such, semi-separable MDP's cover a broad class of problems that can be realistically computed. LP's similar to (7) also lend themselves to row or column aggregation such as in Zipkin [7], which can be used to obtain "good" policies for quite large problems.

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AGGREGATION AND OTHER REDUCTIONS FOR SEMI-SEPARABLE

MARKOV DECISION PROCESSES: THE LINEAR CASE

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February 1978

DRAFT FOR COMMENT

I. Introduction

In a series of recent papers, I show how a semi-separable Markov decision process can be reduced to a problem with n constraints (the number of states) and n lower bounds. If $x \in X$ is a state, and $y \in X$ is a feasible decision, then a process is "semi-separable" (Mendelssohn 1978a)

$$p_{x,j}^y = p_j^y \quad \text{for all } x, j \in X; \text{ and all } y$$

where $p_{x,j}^y$ is the transition probability to state j . Let $f_0, f_1, \dots, f_n$ be the optimal values of the Markov process, and let $v_0 = f_0$; $v_1 = f_1 - f_0, \dots, v_n = f_n - f_{n-1}$. Then I show the LP that solves the problem can be formulated as:

$$\begin{aligned} \min \quad & \sum_{x=0}^n (n+1-x)v_x \\ \text{s.t.} \quad & Av \geq b \\ & v_i \geq b_j^* \end{aligned} \tag{1.1}$$

where the $j+1$ element of b is the return from remaining in state j , b_j^* are simply determined lower bounds, and the j^{th} row of A is:

$$\left(1-\alpha, 1-\alpha \sum_{i=1}^n p_i^j, \dots, 1-\alpha \sum_{i=j}^n p_i^j, -\alpha \sum_{i=j+1}^n p_i^j, \dots, -\alpha p_n^j \right).$$

(see Mendelssohn 1978a for details). In Mendelssohn (1978b), I use the structure of this reduced LP to show how to easily recover an optimal policy from a solution to (1.1), and also to describe qualitative properties of an optimal policy for a wide class of semi-separable processes.

In this paper, I focus on a special case; where the decision set $Y(x)$ for each $x \in X$ is defined as:

$$Y(x) \equiv \{y : 0 \leq y \leq x\} \quad (1.2)$$

and the return is linear, that is:

$$G(x, y) = h \cdot (x-y); h \geq 0 \quad (1.3)$$

This is an example of a separable problem considered by Denardo (1968). However, (1.1) is a smaller problem than the equivalent problem in Denardo; and can be used to obtain even greater reductions in problem size.

In Mendelssohn (1978b), I show that a separable problem satisfying (1.2) and (1.3) always has a base stock policy optimal, if an optimal policy exists. Also, in the linear case, each b_j^* is identically h . the lower bounds can be removed by substituting $v_i' = v_i - h$ for $i = 1, \dots, n$. Before stating theorem 1, a lemma is needed.

Lemma 1.1 Let x be a nonnegative random variable defined on $[0, b]$, where $b < \infty$, and $F(x)$ its cdf. Then:

$$E(x) = \int_0^b [1 - F(x)] dx$$

Proof. See Karlin and Taylor (1975), p. 38.

□

Theorem 1.1 Assumption (1.2) and (1.3) imply the LP given (1.1) is equivalent to:

$$\begin{aligned} & \text{minimize } \sum_{x=0}^n v'_x \\ & \text{s.t. } Av \geq b \end{aligned} \tag{1.4}$$

where $b^i = \alpha E(s[i]) - (i+1)h$; and $s[i]$ is the transition function from state i .

Proof. By the substitution, $v_i = v'_i + h$. At i , this gives $A^i v$ and terms multiplies by h .

$$h \cdot \left((i+1) - \alpha \left(1 + \left(1 - p_0^i \right) + \left(1 - p_0^i - p_1^i \right) + \dots + \left(1 - p_0^i - p_1^i - \dots - p_n^i \right) \right) \right)$$

The inner terms are just $(i+1) - \alpha \sum_{i=0}^n (1 - F(i)) = (i+1) - \alpha E(s[i])$
by lemma 1.1.

□

It is interesting to note that the $(i+1)^{\text{st}}$ RHS is greater than the i^{th} , if and only if:

$$E(s[i+1]) - E(s[i]) \geq \frac{h}{\alpha} \tag{1.5}$$

In a continuous state version, this is equivalent to:

$$\frac{d}{di} (Es(i)) \geq \frac{1}{\alpha} \tag{1.6}$$

Equality in (1.6) is the two-period base stock size. In each row i of A , v^i is added to the row before. The algorithm checks that this "weighted derivative" is greater or less than the change in the two-period result. A related result can be found in Mendelssohn and Sobel (1977).

II. Reducing the Size of the LP

For many problems, even (1.4) will be a very large LP. Luckily, it is possible to greatly reduce (1.4). It is convenient for this discussion to let $b \equiv 0$, and retain the lower bounds $v_1 \geq h$.

Often it is known a priori that the base stock size lies in the interval (j^L, j^u) . This suggests it may be possible to aggregate all the variables below j^L and all the variables above j^u . Theorem 2.1 states that the variables above j^u may be aggregated without loss of optimality; the variables below j^L may be aggregated but possibly with loss of optimality. However, the base stock size will still be in (j^L, j^u) .

Aggregate variables by letting:

$$c^u = \frac{1}{n-j^u+1} \left(\sum_{i=j^u}^n (n+1-i) \right); \quad c^L = \sum_{i=0}^{j^L} w^i (n+1-i)$$

$$\text{where} \quad w^k = \left(\left(1 - \alpha \sum_{i=k}^n p_i^{j^L} \right) / \sum_{i=0}^{j^L} \left(1 - \alpha \sum_{k=i}^n p_k^{j^L} \right) \right)$$

$$\text{and let} \quad q_i^u = \frac{1}{n+1} \left(\sum_{k=j^u}^n a_k^i \right); \quad q_i^L = \sum_{k=0}^{j^L} \left(w^k a_k^i \right); \quad i = j^L, j^L+1, \dots, j^u$$

where a_k^i is the (i, k) element of A . Let $\bar{v}^T = (v^L, v_{j^L+1}, \dots, v_{j^u-1}, v^u)$, and $\bar{A}$ be A with rows 1 through j^L , j^u+1 through $n+1$ eliminated; columns 1 through j^L , j^u+1 through $n+1$ eliminated, and the first and last columns of $\bar{A}$ are q^L and q^u , where $q^{LT} = (q_{j^L}^L, q_{j^L+1}^L, \dots, q_{j^u}^L)$ and $q^{uT} = (q_{j^L}^u, q_{j^L+1}^u, \dots, q_{j^u}^u)$.

Theorem 2.1 The reduced problem:

$$\min \sum_{i=j^L+1}^{j^u-1} (n+1-i)v_i + c^u v_u^u + c^L v^L \quad (1.7)$$

$$\text{s.t. } \bar{A}\bar{v} \geq 0$$

$$v_i \geq h, i = j^L+1, \dots, j^u-1; v^u \geq (n-j^u+1)h; v^L \geq (j^L+1)h$$

has the following properties:

- (i) The base stock size $\bar{j}$ lies in (j^L, j^u) .
- (ii) There is no loss of optimality from aggregating
 $v_{j^u}, v_{j^u+1}, \dots, v_n$
- (iii) The loss of optimality from aggregating $v_0, v_1, \dots, v_{j^L}$
is at most

$$\left[\max_{i=0,1,\dots,j^L} \left\{ (n+1-i) - \bar{u} \bar{A}^i \right\} \right]^+ \frac{\alpha}{1-\alpha} h n,$$

where $\bar{u}$ are the dual variables of the reduced problem.

Proof. A heuristic proof is offered for aggregating the upper variables, since a rigorous proof can be derived as a special case of the lower variables, which is more difficult. Since $j^* \in (j^L, j^u)$, each v_i , $i \geq j^u$,

must be identically h. Also, rows j^u+1 through $n+1$ cannot be tight, hence they can be eliminated. Averaging the transition is justified in that the new process, if it goes to a state greater than j^u , immediately goes at least to j^u (perhaps lower). These are the q_i^u 's.

For the lower variables, it is first necessary to show that j^L will not come out as the solution to (1.7). Suppose it does. The proof is to show that this implies $j^* \notin (j^L, j^u)$ in the original problem. Disaggregate by letting

$$v_i = w_i^L v^L \quad i = 0, \dots, j^L$$

$$v_i = \frac{1}{n-j^u+1} v^u \quad i = j^u, \dots, n+1$$

Then from proposition (1) in Zipkin the disaggregate solution is feasible in (1.1), and equality must hold in row j^L+1 , due to how the weights w_i^L were chosen.

Since $v_{j^L+1}, \dots, v_n$ are at their lower bound and the coefficients on them are negative in that row, it is clear that an improved solution can only be obtained by decreasing $v_0, v_1, \dots, v_{j^L}$. This implies $v_{j^*-1}^*$ is at its lower bound, which contradicts the optimality of j^* .

Part (iii) is equation (4) in Zipkin (1977).

□

Theorem 2.2 suggests a method for finding an optimal policy. Aggregate together all variables with an index less than j^L , greater than j^u , and choose a partition on the remaining states, and aggregate up to each of those points. The following theorem shows that if the

base stock size found from this problem is at the variable representing the i^{th} set of aggregated states, then the true base stock size must lie in that partition.

Theorem 2.2 Assume $j^* \in (j^L, j^u)$. Divide (j^L, j^u) into intervals $(j^L, j^1]$, $(j^1, j^2]$, ..., (j^k, j^u) . Aggregate variables $v^0, \dots, v_{j^L}$ and $v_{j^u}, \dots, v_n$ as in theorem 2.1. Aggregate variables $v_{j^i}, v_{j^{i+1}}, \dots, v_{j^{i-1}}$ similarly to $v_0, \dots, v_{j^L}$, where the weights w^i are chosen from row j^i as in theorem 2.1. Then

- (i) An optimal base stock size for the aggregated problem lies in (j^L, j^u) .
- (ii) If j^i is an optimal base stock size for the aggregate problem, $j^* \in (j^i, j^{i+1})$.
- (iii) The error for the aggregate problem is at most

$$h \frac{\alpha n}{1-\alpha} \sum_{i=1}^K \left\{ \left[\max_{j=j^i, \dots, j^{i+1}-1} \left(n+1-(i+j) - \bar{u}A^{(i+j)} \right) \right]^+ \right\} \\ + h \frac{\alpha n}{1-\alpha} \left(\left[\max_{i=0, \dots, j^L} (n+1-i - \bar{u}A^i) \right]^+ \right)$$

where $\bar{u}$ is the vector of dual variables of the aggregated problem and A^i is the i^{th} column of A .

Proof. Part (iii) is again equation (4) in Zipkin (1977). If part (i) isn't true, then either the row equivalent to staying in j^L of j^u must be an equality. The contrapositive proof in this case is the same as in theorem 2.1.

Suppose j^i is the optimal base size for the aggregate problem. Assume $j^* < j^i$, then a similar contrapositive argument yields that j^* is not optimal in the original problem. If $j^* > j^{i+1}$, then set all the v_i 's, $i \geq j+1$ equal to h . Since this row is an inequality, it must be an equality in the original row. From the form of the disaggregated row, this can only come from changing $v_0, v_1, \dots, v_{j^{i+1}}$, so that $v_{j^*-1} = h$, which contradicts the optimality of j^* .

□

An efficient search technique can now be devised. Aggregate to j^L and from j^u to $n+1$, and some small partition of (j^L, j^u) . If the partition is 10 more variables, this implies initially an LP that is $(12 \times 12)!$ Given the solution to this problem, reaggregate up to j^i and down to j^{i+1} , where j^i is the base stock size from the aggregate problem. Partition this interval as before, and repeat. This algorithm involves solving a series of extremely small LP's. The a posteriori error as given by (iii) can be used as a stopping rule for when it is no longer worth going further.

III. Finding the Interval (j^L, j^u)

Consider the problem:

$$f(x) = \max_{0 \leq y \leq x} \left\{ h \cdot (x-y) + \alpha E \left(f(s[y, D]) \right) \right\}$$

where D is a random variable, and it is assumed that $f(\cdot)$ and $s[\cdot, D]$ are differentiable (perhaps one-sided) and that $f(\cdot)$ is unimodal.

Assumptions that are sufficient for these conditions to be valid are given in Mendelssohn and Sobel (1977).

It is readily seen from that paper or the LP (1.1) that $f'(x) \geq h$. In fact, $f'(x) \equiv h$ if $x \geq y^*$, where y^* is an optimal base stock size. Therefore, if:

$$h \leq \alpha E\left\{h \cdot s^{[1]}[y, D]\right\} = \alpha h E\left\{s^{[1]}[y, D]\right\}$$

the base stock size must be no greater than y . Let y^* be the point where $E(s^{[1]}[y, D]) = \frac{1}{\alpha}$. Then the base stock size for the infinite horizon problem can be no greater than y^* . Let $j^u \equiv y^*$. If $s[y, D] = Ds[y]$, $\Pr\{D \geq 0\} = 1$, and $s[1]$ is continuous, it is easily seen that if $\bar{y}^*$ is the solution to $s'[y] = \frac{1}{\alpha}$, then the infinite horizon problem base stock size is less than $\bar{y}^*$ if $E(D) > 1$, is greater than $\bar{y}^*$ if $E(D) < 1$, and is less than or equal to $\bar{y}^*$ if $E(D) \equiv 1$.

Thus, in comparing the stochastic and deterministic problems, if $\bar{y}^*$ is the deterministic solution, the stochastic solution is more conservative if and only if $E(s[\bar{y}^*, D]) - \bar{y}^*$ is a supermartingale. Using the deterministic solution as the base stock size is more conservative if $E(s[\bar{y}^*, D]) - \bar{y}^*$ is a submartingale. Unless $E(s[\bar{y}^*, D]) \gg \bar{y}^*$, it probably will not be worth it to calculate the stochastic optimum. Zipkin's (1977) results can be used to determine bounds on using this policy. However, particularly in situations where very low stock levels are highly undesirable, such as in managing renewable resources, using the deterministic solution as the base stock size to lower the risk of depletion will probably

outweigh the loss due to this bound. I conjecture that a similar result is valid when linear returns are combined with linear smoothing costs.

In a future paper, these results will be used to analyze several published models relating to managing stochastically varying fisheries.

Acknowledgment

I thank Professor Paul Zipkin of Columbia University for letting me use his unpublished results on aggregating linear programs.

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SUMMARY REPORT OF THE BILLFISH STOCK ASSESSMENT WORKSHOP
PACIFIC RESOURCES

Honolulu Laboratory, Southwest Fisheries Center
Honolulu, Hawaii
5-14 December 1977

Richard S. Shomura (Editor)
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INTRODUCTION

The recent extension of national fishery jurisdiction throughout the world has resulted in an increased interest in developing fishery management agreements, guidelines, and policies. Basic to this development is information on the status of exploited fish stocks. For many species, particularly the pelagic species, the dimensions of the resource base are unknown, since basic research on population dynamics and the collection of adequate fishery statistics have not been accomplished. This is certainly the case for the several species of billfishes even though they are important targets of commercial and recreational fisheries (Table 1). At the International Billfish Symposium convened in 1972 at Kailua-Kona, Hawaii, a glaring shortcoming was the virtual absence of information on stock assessment or fishery dynamics (Shomura and Williams 1974, 1975a, 1975b).

Table 1.--Total Pacific billfish catch (metric tons) by species, 1952-75.

Year	Blue marlin	Striped marlin	Swordfish	Sailfish and spearfish	Black marlin	Total
1952	15,525	4,992	11,339	2,000	1,806	35,662
1953	17,250	3,789	11,689	3,300	3,188	39,216
1954	10,519	7,256	13,392	2,400	5,370	38,937
1955	24,190	7,075	16,485	3,300	5,379	56,429
1956	18,770	7,724	12,584	3,200	6,466	48,744
1957	23,500	7,150	16,243	2,800	6,376	56,069
1958	22,106	8,999	21,341	3,400	4,548	60,394
1959	20,275	8,986	19,663	3,400	3,081	55,405
1960	18,155	7,362	23,409	5,000	2,721	56,647
1961	26,581	10,084	24,286	4,800	3,170	68,921
1962	30,743	13,685	14,604	6,800	4,066	69,898
1963	31,344	16,944	14,133	7,900	3,180	73,501
1964	23,233	23,480	10,112	6,100	2,805	65,730
1965	18,885	24,017	12,949	12,800	4,039	72,690
1966	18,588	20,967	14,601	11,100	3,729	68,985
1967	17,233	22,050	15,649	11,800	2,836	69,568
1968	15,283	27,143	15,230	12,500	2,362	72,518
1969	17,427	21,706	18,934	12,800	2,546	73,413
1970	20,115	24,221	15,727	9,000	2,207	71,270
1971	13,342	24,264	11,037	8,100	2,674	59,417
1972	15,300	14,541	11,029	8,600	3,424	52,894
1973	17,285	15,407	13,791	8,700	3,720	58,903
1974	15,594	14,669	11,664	7,100	3,048	52,075
1975	12,546	16,279	13,376	5,500	2,796	50,497

In early 1977 the National Marine Fisheries Service's Southwest Fisheries Center developed plans jointly with the Western Pacific Regional Fishery Management Council (WPRFMC) to hold a Pacific Billfish Stock Assessment Workshop. The workshop was subsequently expanded to include the Atlantic stocks. Its objective was to produce a report containing a scientific assessment of the status of billfish stocks in the Pacific and Atlantic along with a summary of appropriate background information, supporting analyses, and recommendations. The workshop was held at the Honolulu Laboratory of the Southwest Fisheries Center in December 1977 and consisted of two parts, a Pacific section (5-9 December 1977), which reviewed the Pacific billfish stocks, and an Atlantic section (12-14 December 1977), which treated the Atlantic billfish stocks. The Pacific workshop covered the six species of Pacific billfishes: blue marlin, Makaira nigricans; black marlin, M. indica; striped marlin, Tetrapturus audax; shortbill spearfish, T. angustirostris; sailfish, Istiophorus platypterus; swordfish, Xiphias gladius.

Since by far the greater part of the exploitation of the Pacific billfish resources is carried on by foreign fishers, and consequently foreign governments possess most of the data relevant to their management, the success of the workshop required the joint participation of scientists from the major billfish fishing nations. Scientists from the Honolulu, La Jolla, and Miami Laboratories of the National Marine Fisheries Service, the California Department of Fish and Game, the Far Seas Fisheries Research Laboratory (Shimizu, Japan), National Taiwan University (Taipei, Taiwan), Fisheries Research & Development Agency (Pusan, Korea), and the International Commission for the Conservation of Atlantic Tunas were invited to participate in the workshop. The WPRFMC sponsored the participation of the foreign scientists. The Council has direct interest in the results of the workshop, since it is presently developing a management plan for the Pacific billfishes.

The workshop agenda is shown as Appendix A. Appendix B lists the participants, and Appendix C gives the titles and authors of workshop documents.

Brief summaries of the Pacific billfish stock appraisals and recommendations for improvement of fishery statistics, research, and management are provided in the next few sections. These are followed by the several rapporteurs' reports (Appendix D), which provide detailed discussions of the stock assessments. Results of the Atlantic section will be provided in a separate report.

Data Limitations

A complete understanding of the effects of fishing on fish stock productivity and catch requires a knowledge of growth rates, mortality rates, reproductive rates, and other vital determinants of population dynamics. Unfortunately, in the case of Pacific billfishes such detailed information has not been acquired. Except for a very limited amount of data on size composition and some estimates of growth rates, the only kinds of information available for stock assessment purposes are statistics

on nominal fishing effort and catch. Under these data limitations the billfish stocks were assessed using catch per unit effort (CPUE) and effort trends, as well as the surplus production approach popularized by M. B. Schaefer in the 1950's and improved most recently by Fox (1975).

In using the production model we made two fundamental assumptions concerning the catch and effort data:

(1) the CPUE is proportional to average stock abundance, with the ratio of CPUE to abundance remaining constant over the period of analysis, and

(2) the total catch is known.

Violation of these assumptions was suspected for certain billfish stocks, and known to occur in others. In the latter cases no attempt was made to fit a production model or to estimate a maximum sustainable yield (MSY).

With respect to CPUE, the statistic used in all analyses was the catch per thousand hooks fished in the Japanese pelagic longline fishery, a fishery which generally concentrates on tunas and harvests billfishes only incidentally. Changes in the construction or deployment of the longline gear, shifts in fishing strategy or target species, and changes in availability of the fish to the gear are some of the factors which may alter the ratio of CPUE to average abundance. For example, in the North Pacific, a reduction in nighttime longlining activity targeted specifically on swordfish is almost certainly responsible for a sharp drop in the average swordfish CPUE in that area since the early 1960's. The assessment of the North Pacific swordfish stock is therefore complicated, because the effects of the change in fishing strategy on the ratio of CPUE to abundance are unknown. Similar problems may exist in the assessment of other species.

In the case of total catch, there are generally reliable figures in numbers of fish for the Japanese tuna longline fleet, which accounts for most of the overall harvest and dominates the catch statistics of most billfish species. An exception is the Japanese catch of sailfish and shortbill spearfish, which is reported as a combined total in the longline statistics. In addition, there are serious problems in estimating the total weight of billfishes taken in the inshore or coastal fisheries which use other kinds of gear, e.g., gill nets, and in determining the total catch of other major distant-water longline fleets, particularly the catch of Korean vessels. Where biased catch estimates are suspected, the magnitude of bias may vary from year to year, creating serious problems in interpretation of catch-effort relationships.

Aside from the major assumptions about the catch and effort data, there are several other important conditions which must be met if the production model analysis is to be valid. The most important of these is that the data refer to a single stock of the species under consideration. Stock units for the Pacific billfish populations were selected on the basis of limited evidence concerning larval distribution, seasonality and locations of spawning, catch rate distribution, and tag return

pattern. The validity of the stock boundaries assumed for this report remains to be established.

Other critical assumptions of the production model are discussed in detail by Fox (1975). When these are considered along with the ones discussed above, it is clear that the production model analysis and the resulting estimate of MSY can give at best only very rough approximation on the status of a fish stock and the effects of fishing effort on yield. The stock appraisals summarized below and discussed in greater detail in the rapporteurs' reports should be judged in this context.

SUMMARY OF STOCK APPRAISAL

Blue Marlin

A single Pacific-wide stock of blue marlin is assumed. Total harvest in 1975 was approximately 12,500 metric tons (MT), with about 80% taken by the longline fleet of Japan. CPUE has decreased steadily since the early 1950's, while total effective fishing effort has increased. Production model analysis gives an MSY estimate of about 22,000 MT, which is associated with an effective fishing effort equal to about 50% of the 1975 total effective effort. The Pacific blue marlin stock is judged to be overfished.

Black Marlin

Stock structure of black marlin is unknown, but the restricted coastal distribution of the species and the occurrence of isolated areas of high catch rates suggest the possibility of more than one stock in the Pacific. Furthermore, there is a strong likelihood that movement of black marlin between the western Pacific and the eastern Indian Ocean occurs. The total Pacific catch in recent years has been estimated at around 3,000 MT. Stock assessment is complicated by underestimation of total catches, particularly those made by the Republic of China fleet. For this reason no estimate of MSY is available; however, sharply declining catch rates during the 1950's and a more gradual reduction of apparent abundance since the early 1960's suggest that increased fishing effort would, at best, produce only a small increase in average catch. Until better estimates of total catch are obtained, the status of black marlin harvests cannot be reliably ascertained.

Striped Marlin

Striped marlin total catches increased steadily from nearly 5,000 MT in 1952 to 24,000 MT in 1965. From 1965 to the early 1970's, the catches remained in the 20,000 to 27,000 MT range. In 1972 striped marlin catches dropped to 14,500 MT and remained between 14,000 and 16,000 MT through 1975.

The stock structure of the Pacific striped marlin is unclear; however, evidence based on distribution of catch rates and other factors suggests the population could consist of either (1) separate north and south stocks or (2) a single unit stock for the entire Pacific Ocean.

Estimated MSY is 24,000 MT in the case of a single Pacific-wide stock. Current assessments indicate that the stock(s) of Pacific striped marlin is in good condition and not in need of restrictive management.

Swordfish

Most of the catch of swordfish from the Pacific Ocean is landed by the Japanese longline fleet and is caught in the northwestern Pacific. The total Pacific catch increased from 11,000 MT in 1952 to a record high of 24,000 MT in 1961. The catch then declined abruptly to about 15,000 MT in 1962 and has leveled off at an average of 14,000 MT since 1962.

The stock structure of the Pacific swordfish population is not clearly understood. Current opinion is that the population consists either of a single Pacific-wide stock or of three separate stocks: the latter with centers of concentration in the northwestern, southwestern, and eastern Pacific. The MSY calculated from the production model analysis assuming a single Pacific-wide stock is 20,000 MT, compared to the current catch level of about 14,000 MT. Since present fishing effort is about 20% below the effort required to take the MSY, the fishery does not appear to be overexploiting the stock, and the stock is in good condition.

No individual estimates of MSY are available in the case of three separate stocks.

Shortbill Spearfish

The major longline fisheries report the catches of shortbill spearfish together with catches of sailfish. Very little of the combined catch, however, consists of shortbill spearfish. Since the shortbill spearfish commands the lowest price among the billfish caught by longline gear, catches of this species are not consistently reported. The amount of shortbill spearfish reported is probably an underestimate of the actual catch.

The stock structure of shortbill spearfish is not known; however, the catch rates are relatively high around lat. 20°N and 20°S and low at the equator, thus suggesting a possible North Pacific stock and a South Pacific stock.

Estimates of MSY for the stock(s) of shortbill spearfish are not available due to the unreliable catch statistics. Assumed catch rates of this species from longline data suggest that the stocks are currently at a relatively high level of abundance and the species is probably underutilized.

Sailfish

Although the catches of shortbill spearfish and sailfish are reported combined, the bulk of the catch consists of sailfish. The estimated sailfish-spearfish catch increased gradually from 2,000 MT in 1952 to 6,100 MT in 1964. It then increased markedly to a record high level of 12,800 MT in the 1965-69 period. From 1970 through 1975 the catch declined to about 5,500 MT.

Based on distribution of catch rates, the sailfish in the Pacific is assumed to consist of two stocks--an eastern Pacific stock and a western Pacific stock. In the western Pacific the catch rates of sailfish has shown a decline since 1959. The 1975 catch rate of two fish per 10,000 hooks is the lowest average rate recorded for the western Pacific fishery. The CPUE for the eastern Pacific fishery increased sharply between 1960 and 1965 to about 200 fish per 10,000 hooks, fluctuating downward to about 110 fish per 10,000 hooks in 1975.

Estimation of MSY for sailfish was not attempted because there is yet no reliable method of separating the combined catch by species. The patterns in catch rates and associated nominal fishing effort, however, suggest that the sailfish stock(s) are not in a bad shape.

SUMMARY OF RECOMMENDATIONS

Statistics

The statistics needed to accurately assess the conditions of a fish stock and to evaluate the effects of fishing include estimates of total catch, catch and effort, and data on the size-, sex-, and age-composition of the catch. Except for catch and effort statistics from some segments of the longline fishery, required data are virtually nonexistent for billfishes. Even with the available catch and effort data a number of shortcomings were noted at the workshop. These were (1) incomplete catch and effort records for certain commercial fisheries, e.g., the Korean longline fishery; (2) the virtual absence of recreational billfish catch and effort data, e.g., the Australian and United States recreational fishery; (3) combining of sailfish and shortbill spearfish catches in the basic logbooks maintained by the Japanese longline fleet; and (4) reporting of catch in different units, e.g., round weight, dressed weight, or number.

The workshop recommended that all nations with billfish fisheries be urged to establish new sampling programs and procedures to insure the collection of adequate statistics including (1) total catch by species, gear, type of fishing operation, and ocean region; (2) total nominal effort by gear, type of fishing operation, and ocean region; (3) CPUE by effort, small area-time strata, gear, and type of fishing operations; and (4) size and sex composition of the catches by species and by small area-time strata.

Research

Appraisals of fish stock conditions rely on availability of basic biological information and adequate statistics describing the fisheries over several years. For billfishes, such basic information and data are not adequate for comprehensive stock appraisals. The present assessment of billfish stock is based on catch and effort data from the Japanese longline fishery and estimates of Pacific-wide catches. The lack of adequate data permitted only tentative assessments of the various billfish stocks. These assessments were based on assumed stock structures, and computed measures of effective fishing effort, a statistic which is

assumed to be proportional to fishing mortality rates. These assumptions are difficult to test and verify because they require collections of extensive and detailed data, or long and expensive experimentation. It is possible, however, to use computer simulation models to examine the sensitivity of stock assessment conclusions and management advice to changes in assumptions, e.g., doubling the effective fishing effort. The cost of this kind of analysis is expected to be modest and should provide valuable guidance for research planning.

The workshop recommended that countries be urged to support modeling and computer simulation analyses as a high priority research task.

Another high priority research task identified at the workshop was the need to define the stock structure of the various species of billfishes. Proper assessment and management of the billfish resources will require some understanding of stock structure. While tagging programs provide some of the necessary information, the low catch rates of commercial and recreational fisheries suggest that other techniques are probably more suitable, e.g., immunogenetic methods.

The workshop also recognized the need for the application of other analyses to the billfish stocks, e.g., yield-per-recruit analysis. Since these approaches require age and growth information the workshop recommended that research be undertaken to determine the age of billfish and to establish age-size relations.

The workshop noted that assessments of the billfish resources could be improved by conducting a further detailed study of the longline fishery and a more complete treatment of other fisheries for billfishes, including the Japanese gill net fishery. For the longline fishery it was noted that changes in fishing method and strategy, such as the recent increased effort by deep-fishing longline gear and the reduction in the longline fishery for swordfish, could have a marked influence in the computation of effective fishing effort. The workshop recommended that countries having access to extensive historical data undertake studies to define these changes and their relation to effective fishing effort.

Management

Sophisticated management advice for the Pacific billfish fisheries is difficult to formulate at this time because of (1) the lack of adequate data needed to fully understand the fish stocks and fisheries and (2) the absence of effective international arrangements for conservation of highly migratory species. Production model analyses of available data, however, provide a basis for tentative management advice.

The available data on the Pacific blue marlin stock suggest that this species is overfished. Whether the overfished condition is due to recruitment overfishing or yield-per-recruit overfishing is not known. If the condition is caused by recruitment overfishing, the situation is probably very serious and appropriate action should be taken to provide for additional escapement as a means of increasing the spawning stock. If, on the

other hand, the condition is caused by yield-per-recruit overfishing, the situation is not as serious, but restrictions on effort and/or minimum size at capture would be required to improve the average yield.

The stocks of Pacific striped marlin and swordfish appear to be exploited at levels close to estimated MSY. Nevertheless, the stocks appear to be in good condition and from a biological viewpoint the fisheries are not in need of restrictive management. However, these species should be monitored closely for signs of overfishing.

The status of the stocks of black marlin, sailfish, and shortbill spearfish is less certain. It is conceivable that a detailed reassessment of historical data may provide the basis for separating the combined sailfish-shortbill spearfish catch data, thus permitting appropriate production model analyses to be undertaken. Similarly, improved estimates of total catch may lead to better assessment of the black marlin resources. In the meantime no restrictive management is deemed necessary from a biological viewpoint.

With respect to management institutions, the widespread distribution and migratory tendencies of the billfishes suggest that effective management can only be achieved by a broad-based management program, covering the entire range of the stocks. To date, a management mechanism of this nature does not exist in the Pacific.

The workshop recommended that countries harvesting billfishes in the Pacific support continuing efforts to assess the stocks and assist in formulating management options which will lead to optimal utilization of the billfish resources.

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Appendix A

AGENDA

SESSION I - Pacific Billfish Resources (5-9 December 1977)

1. Opening remarks (R. S. Shomura, chairman)
2. Adoption of agenda
3. Overview of United States, Japan, Republic of Korea, Republic of China fisheries
4. Review and discussion of data base
5. Review and discussion of billfish life history statistics and parameters
6. Stock assessments
 - a. Blue marlin, Makaira nigricans
 - b. Striped marlin, Tetrapturus audax
 - c. Sailfish, Istiophorus platypterus, and shortbill spearfish, Tetrapturus angustirostris
 - d. Swordfish, Xiphias gladius
 - e. Black marlin, Makaira indica
7. Review and reanalysis of data as needed
8. Final discussion of assessments and recommendations to be included in summary report
9. Write-up of summary report
10. Review and approval of summary report
11. Closing remarks (R. S. Shomura)

SESSION II - Atlantic Billfish Resources (12-14 December 1977)

1. Adoption of agenda
2. Overview of United States, Japan, Republic of Korea, Republic of China fisheries
3. Review and discussion of data base
4. Review and discussion of billfish life history parameters
5. Stock assessments
 - a. Blue marlin, Makaira nigricans
 - b. White marlin, Tetrapturus albidus
 - c. Sailfish, Istiophorus platypterus/longbill spearfish, T. pfluegeri
 - d. Swordfish, Xiphias gladius
6. Summary and write-up of summary report
7. Review and approval of summary report

Appendix B

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Appendix C

WORKING PAPERS

Session I - Pacific Billfish Resources

- BSAW/WP1 Wetherall, Jerry A., and Marian Y. Y. Yong.
 An assessment of Pacific billfish stocks based on the
 generalized production model.
- BSAW/WP2 Ueyanagi, Shoji.
 A review of the Japanese commercial fisheries for
 billfishes.
- BSAW/WP3 Honma, Misao, Tamotsu Yonemori, and Shoji Ueyanagi.
 Drift gill-net (ōme ami) fishery in Japanese waters and
 its possible influence on the stock of the North Pacific
 striped marlin.
- BSAW/WP4 Suzuki, Ziro, and Misao Honma.
 Stock assessment of billfishes in the Pacific.
- BSAW/WP5 Yuen, Heeny S. H.
 Overview of fisheries for billfishes in Hawaii.
- BSAW/WP6 Bartoo, Norman W.
 A brief review of billfish life history and population
 dynamics parameters.
- BSAW/WP7 Squire, James L., Jr.
 Review paper on billfish sportfishing catch rates,
 weight/length/sex data, and tagging effort and
 recoveries.
- BSAW/WP8 Bell, Robert R.
 The California swordfish fishery.
- BSAW/WP9 Sakagawa, Gary T.
 The Pacific swordfish resource.
- BSAW/WP10 Yang, Rong-Tszong.
 Billfish fishery in Taiwan.

Appendix D

RAPPORTEURS' REPORTS

BLUE MARLIN, MAKAIRA NIGRICANS

Heeny S. H. Yuen and Peter M. Miyake

I. REVIEW OF FISHERIES DATA

The blue marlin, Makaira nigricans, has been characterized as the predominant marlin of the central tropical Pacific. They are widely distributed in the Pacific Ocean: from the American to the Asiatic Continents between approximately lat. 45°N and 45°S (Figure 1). Blue marlin are taken primarily by longlines and small numbers are taken by gill nets and harpoons. Japan, the Republic of China (Taiwan), and the Republic of Korea have large Pacific-wide longline fisheries that take blue marlin. Blue marlin are caught by recreational fishermen in Hawaii, from Mexico to Ecuador in the eastern Pacific, and from Australia to Japan in the western Pacific.

A. Catch Trends

The total annual Pacific catch of blue marlin from 1952 to 1975 rose irregularly and reached a peak of 31,300 metric tons (MT) in 1963 and declined irregularly thereafter (Table 1; Figure 2). The annual catches have been consistently greater in the North Pacific than in the South Pacific; the North Pacific catch in 1975 was 84% of the Pacific total.

B. Effort Trends

Effective fishing effort increased from about 50 million hooks in 1952 to about 260 million hooks in 1963 and fluctuated around 200 million hooks from 1964 to 1975 (Figure 3).

C. Catch Rate Trends

Catch per effort (CPUE) steadily declined from about 3.0 fish/1,000 hooks in 1952 to about 0.5 fish/1,000 hooks in 1975 (Figure 3). The 1975 CPUE was the lowest value recorded for blue marlin.

II. STOCK STRUCTURE

Blue marlin appear to comprise a single, equatorially centered stock in the Pacific. Concentrations of blue marlin alternately appear at higher latitudes on both sides of the equator during the respective summer periods. Evidence for a unit stock assumption is the apparently single, large spawning area in the western Pacific, including areas of high spawning densities in the west and declining densities eastward. As is true of the other billfishes confirmation of the blue marlin stock structure hypothesis is needed.

III. POPULATION PARAMETERS

The available population parameters are shown in Table 2 of the Swordfish Rapporteur's Report. Like the other billfishes, basic data on mortality rates, age and growth, fecundity, etc., are tentative and need to be improved. The inability to confirm age estimates of blue marlin has hampered stock assessment work. The existing growth equation should be verified so that age composition of the catch can be computed when length composition data become available.

IV. STOCK ASSESSMENT

Pacific-wide catch and effort data (Table 1) were used to assess the current status of the assumed single blue marlin stock.

The relation between CPUE and effective effort trends (Figure 3) provides indications of the condition of the stock. The CPUE from 1952 to 1975 steadily declined from 3 fish/1,000 hooks in 1952 to 0.5 fish/1,000 hooks in 1975, including only minor fluctuations. Over the period from 1952 to 1963, effort rose steadily, increasing by a factor of 4. Subsequently, a relatively constant, high level of effective effort was evident from 1964 to 1975. The steady decline in CPUE over the last 10 years in the presence of a fairly constant effort indicates a potential problem with the stock.

A production model was fitted to the 1952 to 1975 data for the entire Pacific (Figure 4). The results project a maximum sustainable yield (MSY) of about 22,000 MT per year at an optimum effort level of 5.5×10^5 hooks/5° square which is approximately equivalent to a total effective effort of 142 million hooks. The 1975 catch of 12,500 MT was taken by an effort of 10×10^5 hooks/5° square or approximately 215 million effective hooks. The model appears to fit the data quite well.

Although it is not possible to perform additional analyses to estimate yield-per-recruit or recruitment indices, the combined evidence of CPUE and effort trends and production model analysis suggests that the blue marlin stock is being substantially overfished. This overfishing apparently began in the early 1960's and has continued through 1975.

V. OVERALL STOCK APPRAISAL

The evidence of declining CPUE and the result of the production model analysis suggests that the blue marlin stock is being overfished. The present effort is almost twice that needed for MSY.

VI. RECOMMENDATIONS

A. Statistics

To confirm the current appraisal of the blue marlin stock, additional basic data must be obtained. Length composition samples by sex for current catches should be collected, and historical size composition data should be analyzed. Additional catch and effort data should be collected from fleets with presently low coverage rates.

B. Research

The potentially serious condition of the blue marlin stock suggests that additional analyses to confirm the current appraisals are needed. The available age-growth results need to be confirmed. Yield-per-recruit and recruitment indices are needed. These analyses should, if possible, take into account differential catch rates and growth by sex.

C. Management

The production model analysis indicates that the Pacific blue marlin stock has been substantially overfished since the early 1960's. Effective fishing effort increased from 1952 to 1962, then essentially leveled off during 1963 to 1975; however, effective fishing effort in 1975 was at the highest level since the beginning of the fishery in 1952 and was almost twice the computed optimum effort. Relative to these effort trends, total yield has been declining since 1963 and CPUE has been declining since 1952.

The total yield obtained in 1975 from this level of effort was the second lowest recorded. Although information on stock-recruitment relations is not presently available for blue marlin, it seems clear that continued fishing at high levels will continue to reduce the abundance of the stock and a recruitment failure will become a distinct possibility.

These warning signs warrant the serious consideration of some form of management for blue marlin. In view of the apparent seriousness of the situation, it was recommended that the monitoring of the status of blue marlin in the Pacific be given the highest possible priority in billfish research.

Table 1.--Blue marlin catches (metric tons) by countries for the Pacific Ocean.

Year	Japan	Taiwan	Korea	Others	Total
1952	15,525				15,525
1953	17,250				17,250
1954	10,253	266			10,519
1955	23,590	600			24,190
1956	18,136	634			18,770
1957	23,030	470			23,500
1958	21,712	394			22,106
1959	19,908	367			20,275
1960	17,825	330			18,155
1961	26,267	314			26,581
1962	29,983	760			30,743
1963	29,434	1,910			31,344
1964	21,323	1,910			23,233
1965	16,675	1,910		300	18,885
1966	16,156	1,910	222	300	18,888
1967	13,944	2,428	461	400	17,233
1968	12,300	2,562	221	200	15,283
1969	14,415	2,371	441	200	17,427
1970	16,976	2,481	453	200	20,115
1971	9,932	2,757	453	200	13,342
1972	11,760	2,787	453	200	15,300
1973	13,252	3,280	453	300	17,285
1974	12,313	2,410	453	418	15,594
1975	9,735	2,229	453	129	12,546

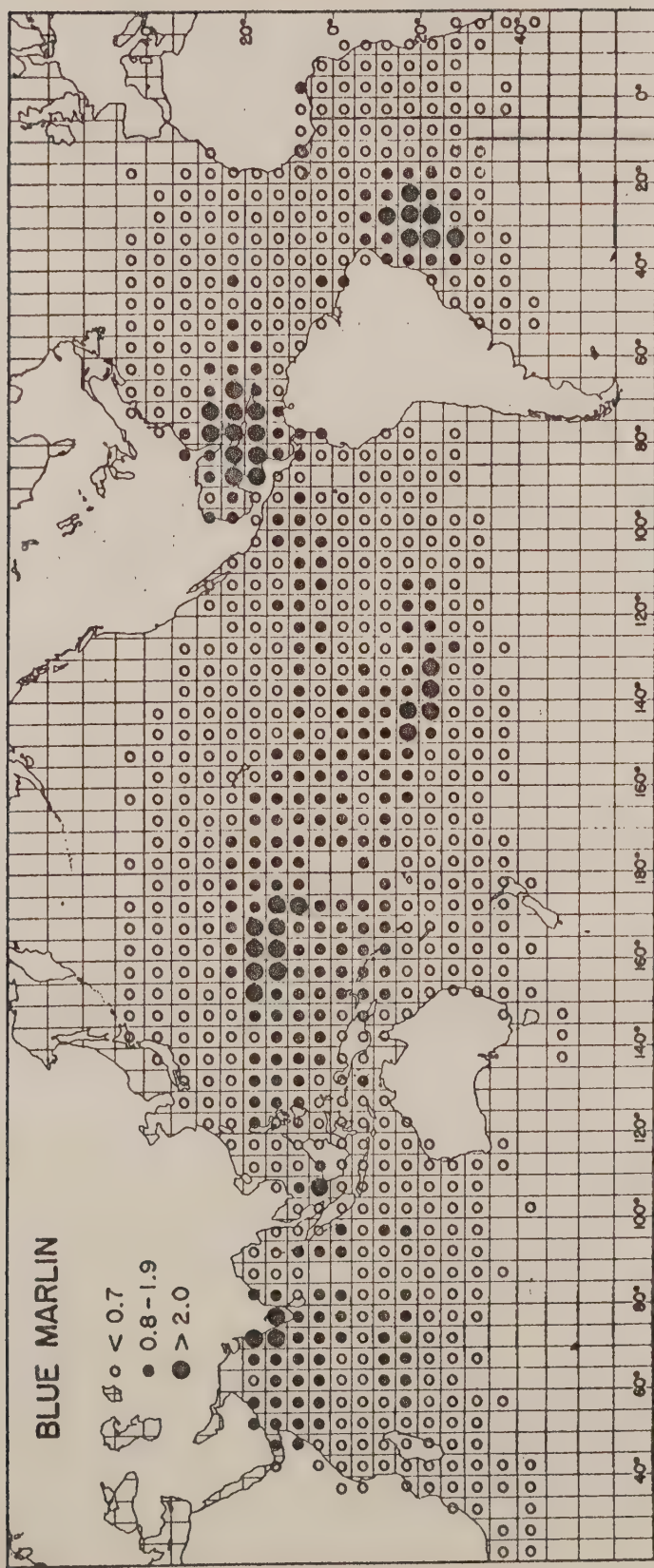


Figure 1.--Distribution of blue marlin in the Pacific Ocean. The circles indicate mean catch rates (number of fish/1,000 hooks).

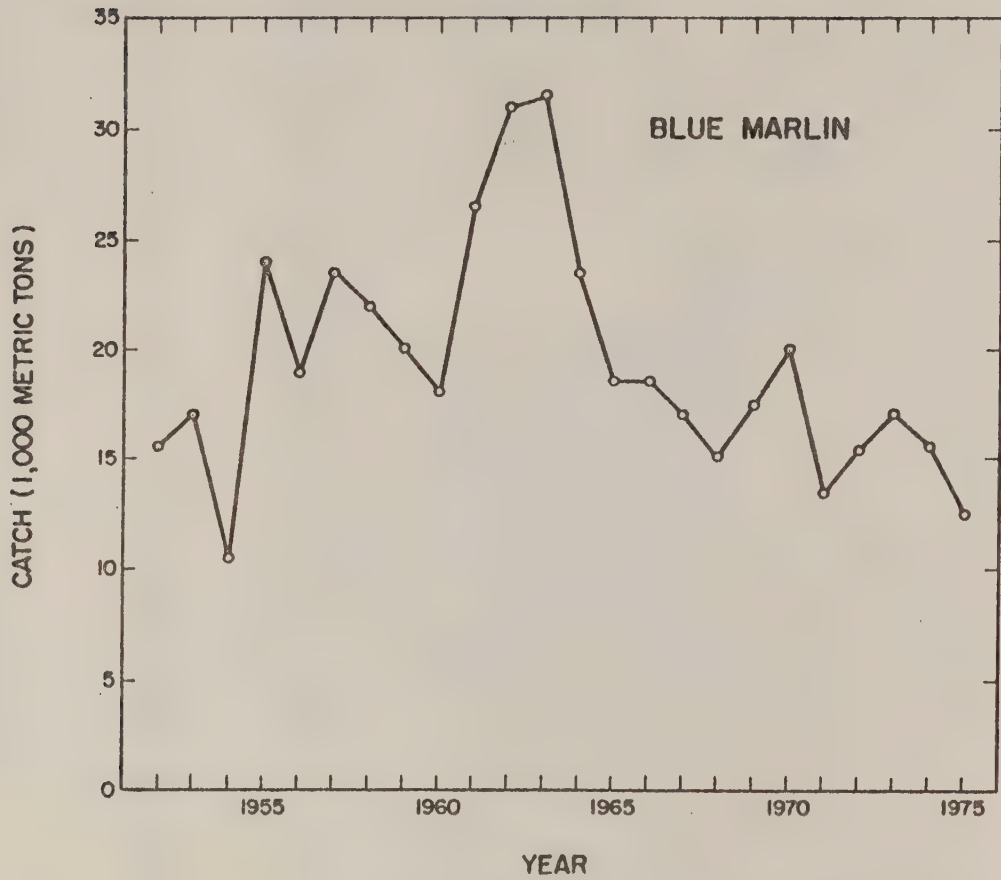


Figure 2.--Blue marlin catch in the Pacific (Suzuki and Honma BSAW/WP4).

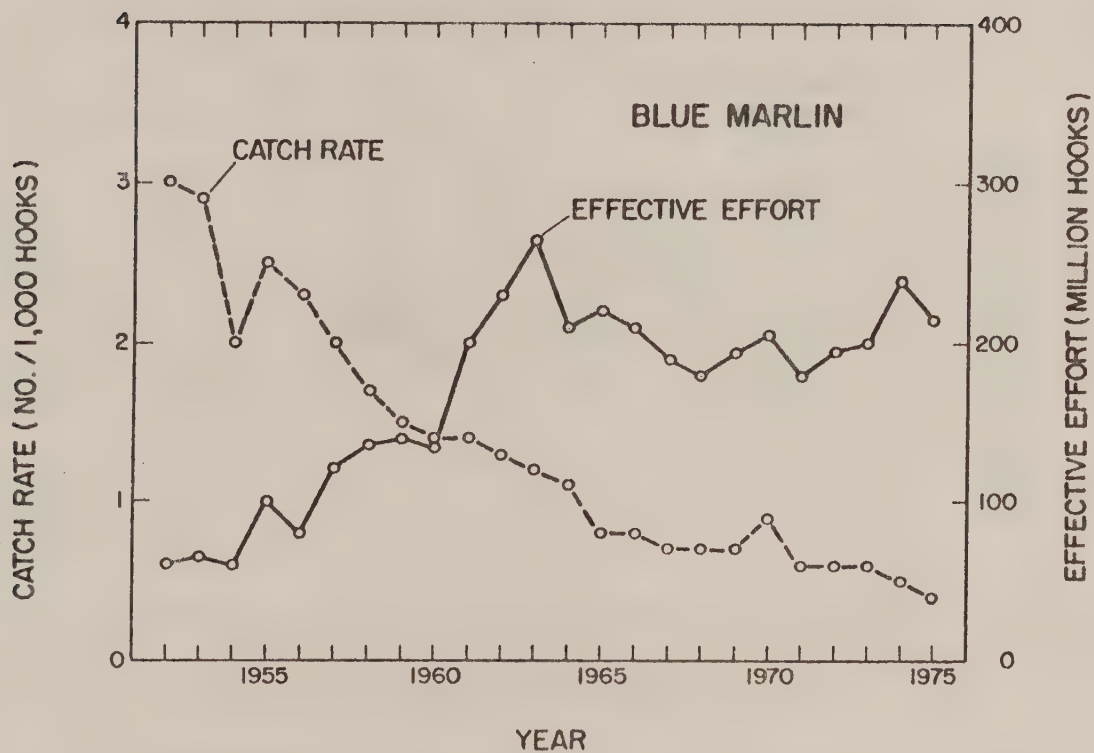


Figure 3.--Catch rate and effective fishing effort for blue marlin in the Pacific (Suzuki and Honma BSAW/WP4).

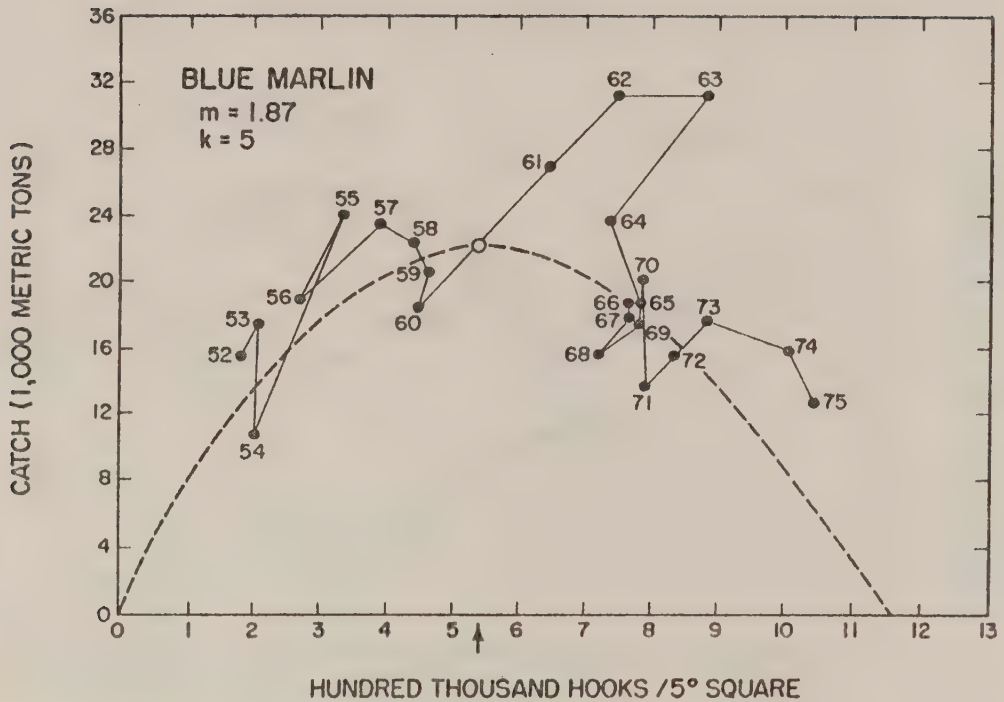


Figure 4.--Relation between catch of blue marlin and effective fishing effort. The equilibrium yield curve is based on the production model.

STRIPED MARLIN, TETRAPTURUS AUDAX

Norman W. Bartoo and Shoji Ueyanagi

I. REVIEW OF FISHERIES DATA

Striped marlin, Tetrapturus audax, are widely distributed in the Pacific Ocean between lat. 50°N and 50°S. The tuna longline catch rates of striped marlin indicate bands of relatively high density across the North and South Pacific which merge in the eastern Pacific to form a horseshoe-shaped pattern of high density (Figure 1).

Striped marlin are caught in the Pacific tuna longline fisheries of Japan, Republic of Korea, and Republic of China (Taiwan), which harvested a combined total catch ranging between 14,000 and 16,000 metric tons (MT) annually in recent years. The catch of these three countries accounts for most of the Pacific striped marlin harvest. In the central North Pacific striped marlin are caught by Hawaiian-based longliners and trollers (including sport fishing boats). The Hawaiian catch is small, once amounting to about 200 MT annually; in recent years it has amounted to only about 50 MT.

Gill nets are also used to catch striped marlin and since 1973 the drift-gill net catches off Japan have increased significantly. More than 3,000 MT or approximately one-third of the total catch from the North Pacific is landed annually by this fishery.

Small amounts of striped marlin are caught by recreational fishermen off California. Estimates indicate an annual catch averaging 40 MT. Off Mexico and Central America, striped marlin are also taken by recreational fishermen. The total catch is not known but may be as high as 200 MT per year.

A. Catch Trends

The Pacific-wide catch of striped marlin (Taiwan, Japan, Korea, and United States combined) rose steadily from approximately 5,000 MT in 1952 to 24,000 MT in 1965 (Table 1, Figure 2). From 1965 to 1971 the catch fluctuated between 20,000 and 27,000 MT. In 1972 the catch abruptly dropped to 14,500 MT and remained between 14,000 and 16,000 MT through 1975.

Catches of striped marlin from the North Pacific area contributed most to the Pacific-wide totals. The North Pacific catch increased slowly from 1952 through 1963, rose markedly to a peak of 21,000 MT in 1968, and since then fluctuated between 9,000 and 18,000 MT (Figure 2). Catches from 1973 through 1975 remained almost constant at near 12,000 MT per year.

Catches of striped marlin from the South Pacific area showed a similar trend but with less fluctuation than in the North Pacific. The catch rose from a few tons in 1952 to a peak of 10,000 MT in 1963, dropped to 5,000 MT in 1964 and began a slow decline to a low of 4,000 MT in 1975 (Figure 2). Annual catches from 1973 through 1975 remained nearly constant at 4,000 MT.

B. Effort Trends

Total effective fishing effort for the entire Pacific (Figure 3) showed an increasing trend from 1952 through 1964. Since then the trend has been relatively flat and fishing effort has been fluctuating between about 100 million and 200 million hooks.

Effective fishing effort in the North Pacific increased from 40 million hooks in 1952 to 180 million hooks in 1964, then declined irregularly to 90 million hooks in 1975 (Figure 3). Effective fishing effort in the South Pacific showed a modest increase between 1952 and 1960, and a substantial increase by a factor of 6 from 1960 to 1963 (Figure 3). Since then it has fluctuated around 100 million hooks. Much of the fishing since 1970 in the South Pacific has been by Korean longliners, for which catch-effort data were not available; consequently the data on fishing effort is less reliable since 1970.

C. Catch Rate Trends

Catch rate of striped marlin for the entire Pacific fishery shows a slow long-term decline (Figure 3). From 1952 to 1975 the catch rate declined approximately 50%.

Catch rate in the North and South Pacific shows long-term declines since the mid-1950's (Figure 3). The decline has been much sharper in the South Pacific than in the North Pacific. The catch rate trend in the North Pacific closely followed that in the entire Pacific. The decline in the South Pacific catch rate was considerable from 1954 to 1957 following the 3 years of rising catch rates. After 1957, the South Pacific catch rate declined in a manner similar to that in both the entire Pacific and the North Pacific.

II. STOCK STRUCTURE

The stock structure of the Pacific striped marlin is not clear. While many hypotheses may be advanced, considering the distributional patterns and other biological data, the two most likely hypotheses are:

1. A single-unit stock in the Pacific.

The single stock hypothesis is supported by the continuous distribution of striped marlin in a horseshoe-pattern.

2. A two-stock structure, where the stocks are separated roughly at the equator into North Pacific and South Pacific stocks with some intermixing in the eastern Pacific (Figure 1).

The two-stock hypothesis is supported by morphometric differences between adults from the north and south regions of the western Pacific (Kamimura and Honma 1958) and perhaps also in the eastern Pacific (Howard and Ueyanagi 1965). Honma and Kamimura (1958) noted that there is a zone of low longline catch rates along the equator which suggests a separation of north and south stocks

Pacific-wide stock, or (2) three separate stocks with centers of concentration in the northwestern (Area 1), southwestern (Area 2), and eastern (Area 3) regions of the Pacific Ocean (Figure 1).

III. POPULATION PARAMETERS

Estimates of basic, critical population parameters for swordfish are lacking. Available estimates are shown in Table 2. They include estimates of growth and mortality rates that are judged to be crude. The difficulty in obtaining reliable estimates appear to be limited by the ability to age swordfish. A reliable aging technique has not yet been developed and most population parameters rely on age-dependent data.

IV. STOCK ASSESSMENT

The condition of the swordfish stocks of the Pacific was evaluated based on different hypotheses about the stock structure of the population: hypothesis 1, a single Pacific-wide stock, and hypothesis 2, three separate stocks. Because of limited data on the stocks the evaluation was restricted primarily to the use of production model analysis.

A. Single Pacific-Wide Stock

The relation of catch and effective fishing effort, assuming a single Pacific-wide stock is shown in Figure 4. The data points fall into two clusters separated by a break between 1963 and 1964, which corresponds approximately to the period when the operational methods in the longline fishery changed in the productive northwestern fishing area. As indicated earlier, longline night fishing which is directed at swordfish, was the predominate manner of fishing in the northwestern region prior to the mid-1960's. Since then, fishing in that region has become more a day operation for tunas rather than a night operation for swordfish.

Production model analysis of the separate clusters of points gave no solution for the 1964-75 data series, and a maximum sustainable yield (MSY) estimate of 20,000 MT per year with 2.2 million hooks/5° square for the 1952-63 data series. Presumably during the 1952-63 period the fishery was more efficient in catching swordfish than during the 1964-75 period. The current (average for 1966-75) catches of about 14,100 MT produced by 1.8 million hooks/5° square, indicate that the fishery does not appear to be overexploiting the stock and that the stock is in good condition.

B. Three Separate Stocks

Complete data for production model analysis, assuming three stocks in the Pacific were not available for examination. An appraisal of the condition of the stocks was therefore based on estimates of apparent abundance from Japanese longline data for 1952-75.

In the northwestern region (Area 1), the longline catches ranged from about 6,800 to 22,900 MT (Figure 5); the catch rates showed a gradual decline from about 20 fish/10,000 hooks in 1958 to 8 fish/10,000 hooks in 1971 (Figure 6). Since 1971 the catch rate gradually recovered to the current level of 12 fish/10,000 hooks in 1975.

SWORDFISH, XIPHIAS GLADIUS

Gary T. Sakagawa and Robert R. Bell

I. REVIEW OF FISHERIES DATA

Swordfish, Xiphias gladius, occur in waters off California, U.S.A. to Chile in the eastern Pacific, throughout the central Pacific, and in waters from Japan to Australia in the western Pacific (Figure 1). They are caught by surface gears (harpoon, gill nets, and handlines) and by longlines. Nations participating in the fishery include: United States (harpoon fishery off California); Chile, Mexico, and Peru (coastal handline fisheries); Japan (Pacific-wide longline fishery and a coastal mainly drift-gill net fishery off Honshu and Hokkaido); Republic of China (Taiwan) (Pacific-wide longline fishery and a coastal, primarily longline and harpoon fishery); and Republic of Korea (Pacific-wide longline fishery). Swordfish are not caught in significant quantities by recreational fishermen anywhere in the Pacific.

The surface fisheries are directed to catching swordfish whereas the longline fisheries are generally directed to catching tunas. In certain regions of the northwestern Pacific, however, longlines are set at night specifically for swordfish. This practice has been on a decline since the mid-1960's and most of the sets are now daylight operations directed at tuna with incidental catches of swordfish.

A. Catch Trends

The total annual Pacific catch of swordfish increased from 11,300 metric tons (MT) in 1952 to a record high of 24,300 MT in 1961. Since then the catch has fluctuated within a narrow range of 10,100 to 18,900 MT, averaging 13,800 MT annually (Table 1; Figure 2). Most of the catch is landed by the Japanese longline fleet (about 58% in 1975) in the northwestern Pacific (about 75% in 1975).

B. Effort Trends

Effective fishing effort for Pacific swordfish has fluctuated between 270 million and 550 million hooks (Figure 3). The level in 1975 was about 300 million hooks.

C. Catch Rate Trends

The longest available time series of catch rates is for the Japanese longline fleet. Total Pacific catch rates for this fleet reached a peak of about 10 fish/10,000 hooks in 1958, declined to a low of 4 fish/10,000 hooks in 1967, and since then stabilized at about 5 fish/10,000 hooks (Figure 3).

II. STOCK STRUCTURE

The stock structure of the swordfish population of the Pacific Ocean is not clearly known. Available data on distribution of larvae and on longline catch rates suggest that the population consists of either (1) a single,

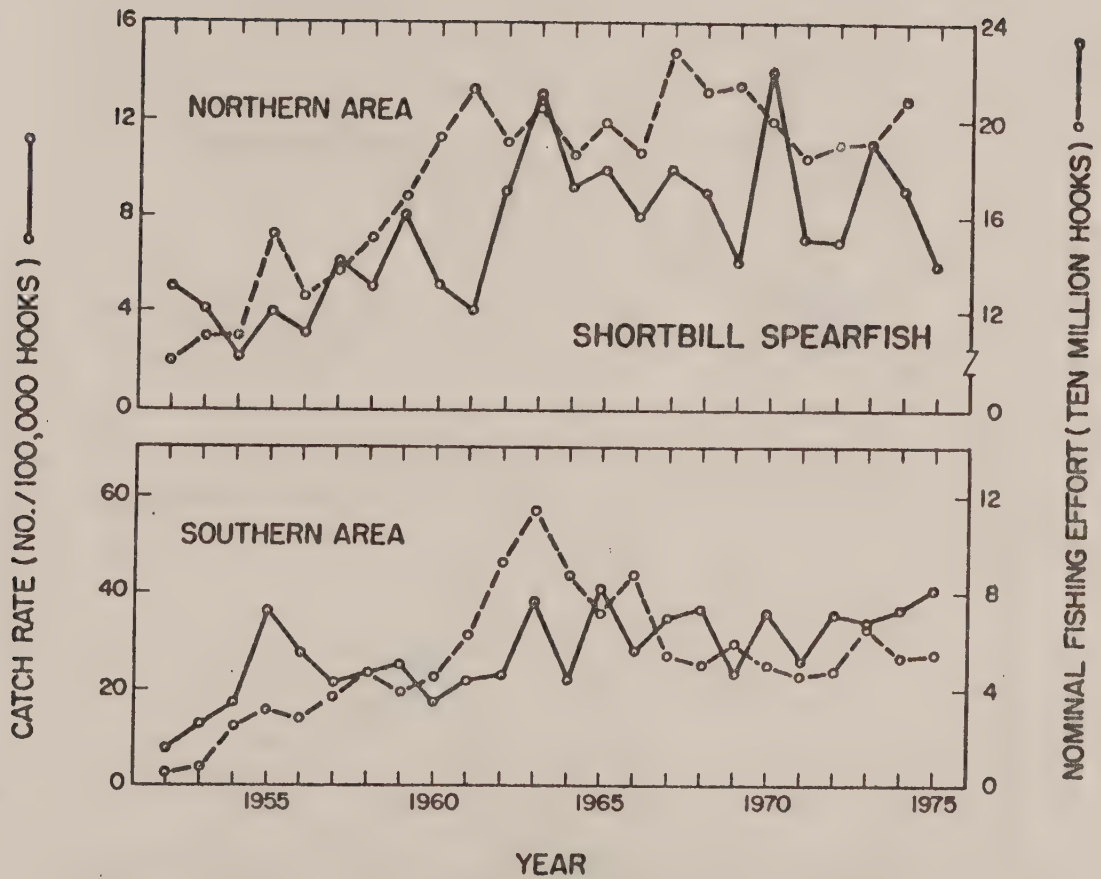


Figure 4.--Catch rates and nominal fishing effort for shortbill spearfish in the Pacific.

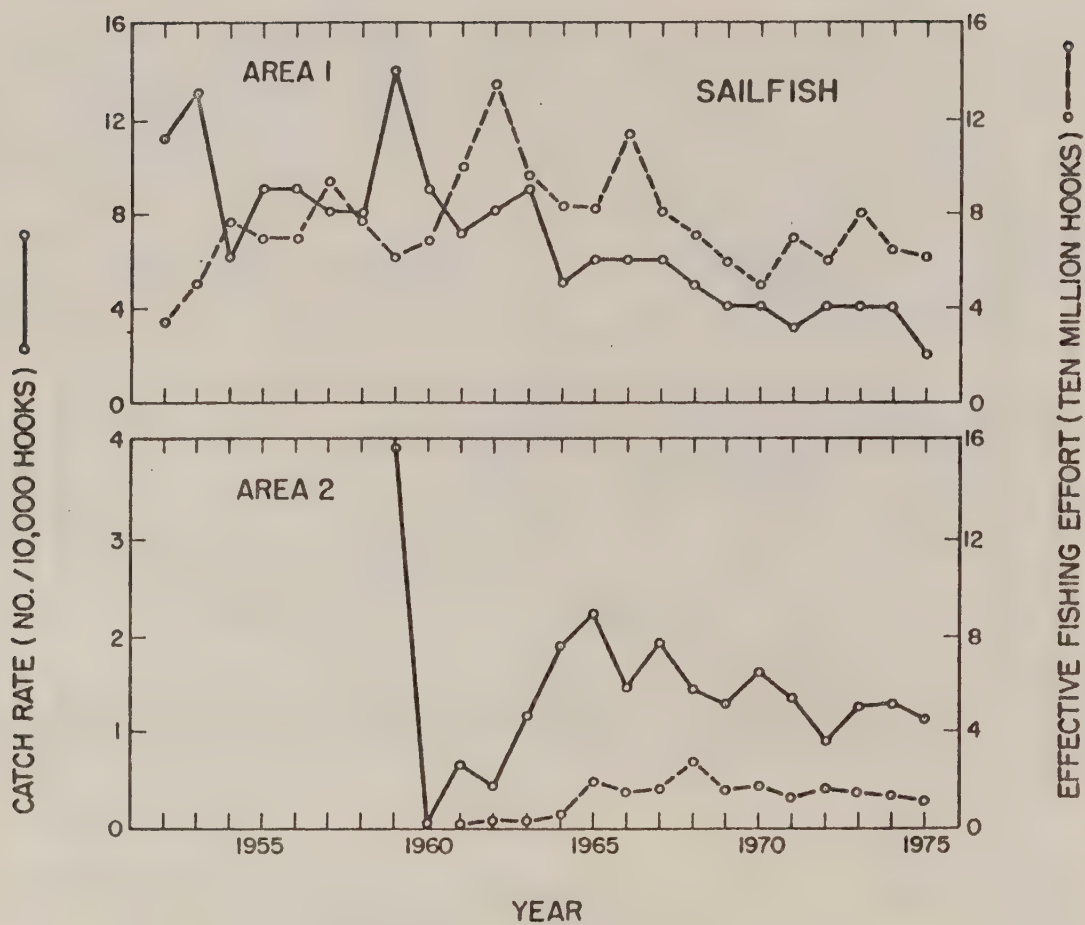


Figure 3.--Catch rates and effective fishing effort for sailfish in the Pacific.



Figure 2.--Catches of sailfish and shortbill spearfish in the Pacific.

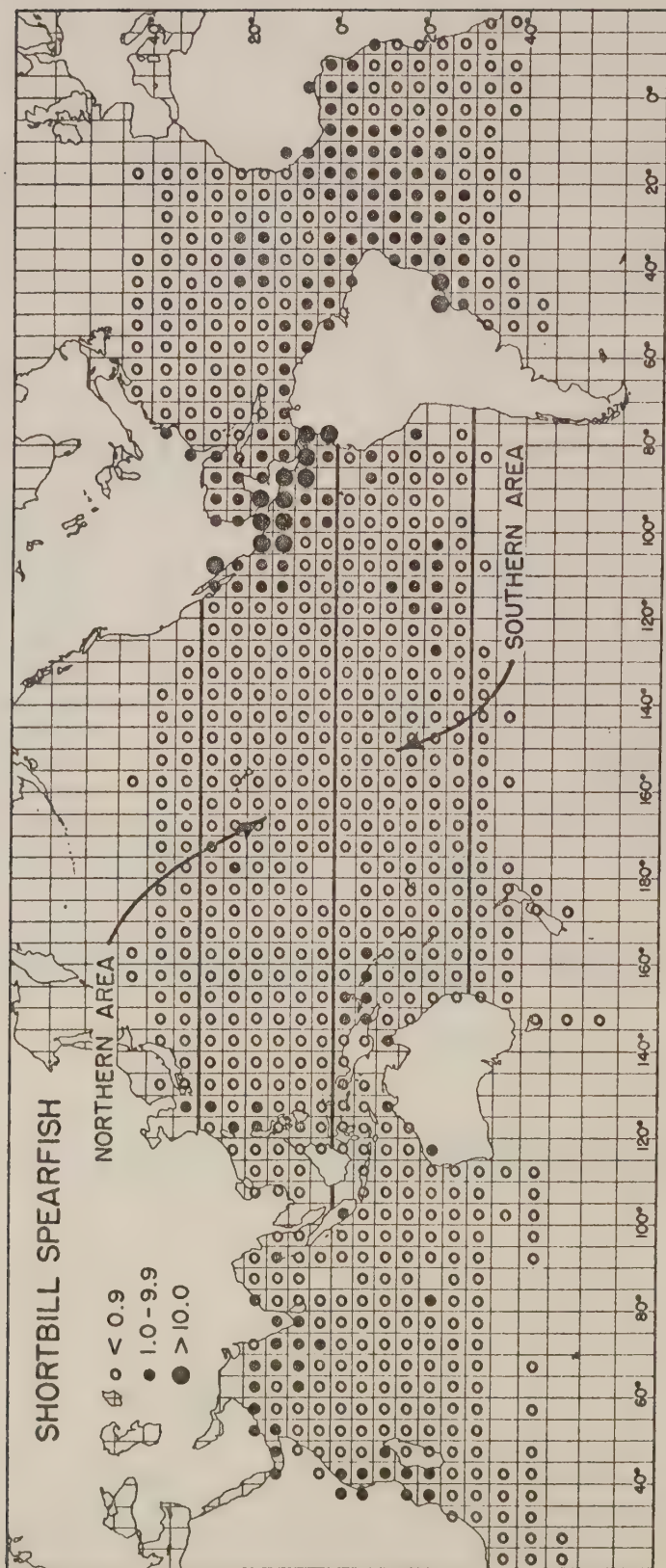


Figure 1B.---Boundaries of suggested shortbill spearfish stocks. The circles indicate mean catch rates (number of fish/1,000 hooks) for shortbill spearfish and sailfish.

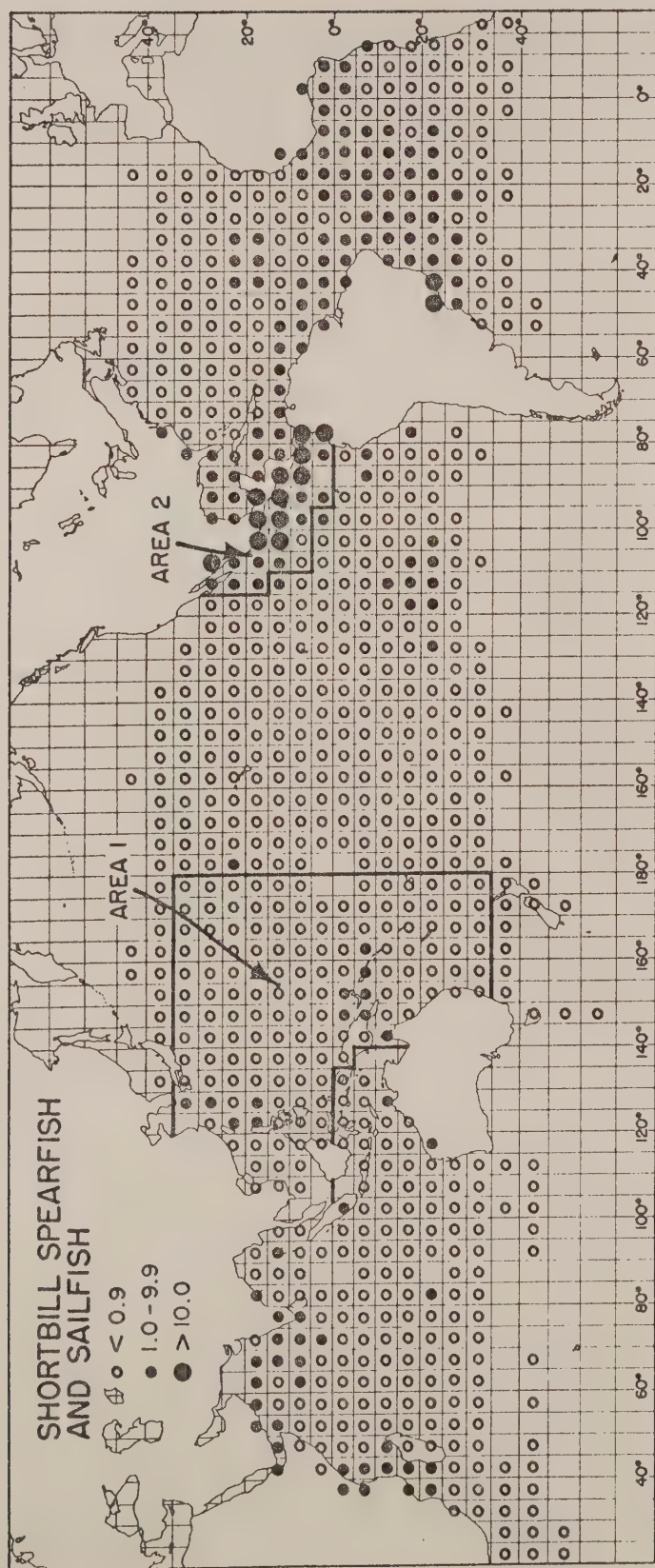


Figure 1A.--Distribution of sailfish and shortbill spearfish in the Pacific. The circles indicate mean catch rates (number of fish/1,000 hooks) for shortbill spearfish and sailfish. Also shown are boundaries of hypothesized stocks of sailfish.

Table 1.--Annual combined landings of Pacific sailfish and shortbill spearfish, 1952-75 by number of fish and metric tons.

Year	Number of fish (10^3)	Metric tons (10^3)
1952	72.6	2.0
1953	119.2	3.3
1954	88.2	2.4
1955	120.6	3.3
1956	115.5	3.2
1957	171.6	2.8
1958	122.0	3.4
1959	142.0	3.4
1960	129.2	5.0
1961	152.2	4.8
1962	216.3	6.8
1963	289.3	7.9
1964	250.4	6.1
1965	598.1	12.8
1966	435.3	11.1
1967	487.3	11.8
1968	676.5	12.5
1969	333.2	12.8
1970	466.4	9.0
1971	260.3	8.1
1972	230.0	8.6
1973	304.3	8.7
1974	253.5	7.1
1975	191.3	5.5

It was also recommended that currently available data be analyzed with production model analysis, using different combinations of catch statistics to evaluate biases in catch estimates and the different stock structure hypotheses. These outputs should then be evaluated to determine what additional studies might be needed.

C. Management

A general management recommendation cannot be made at this time. From current analyses of the data, there appears to be no critical management problems with the stocks at this time. However, it is recognized that there has been a substantial decline in catch rate for sailfish. It is recommended that the fisheries be monitored at an increased level and that the evaluation of data be intensified.

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model analysis was not performed. Appraisal of stock condition was therefore based on estimates of apparent abundance as deduced from Japanese longline data.

Sailfish. The substantial decline in catch rate that occurred between 1953 and 1975 in Area 1 suggests that any increase in effort probably will not result in a substantial increase in catch and if further increases in deep longlining occurs, the catch would decrease even if effort remains constant.

Since 1965 there has been a decrease in catch rate in Area 2, although the decline was not as sharp as that in Area 1. Thus, it is possible that an increase in effort may result in a slight increase in catch. However, if effort is switched to deep longlining, the catch could decline without a change in nominal effort.

Shortbill spearfish. The catch rate in both the northern and southern areas has generally increased from 1952 to the present. Therefore, fishing has not resulted in a decline in stock abundance and any increase in effort should result in an increase in catch.

V. OVERALL STOCK APPRAISAL

Catch rates of sailfish in both the western and eastern Pacific declined substantially, and any increase in effort will probably produce little increase in catch.

The catch for shortbill spearfish has shown a general increase, and any increased effort should result in higher catches.

VI. RECOMMENDATIONS

A. Statistics

The workshop recommended that the maintenance of accurate statistics on the catch of sailfish and shortbill spearfish be encouraged and that better estimates be made of the catch of the gill net and recreational fisheries.

B. Research

The workshop recommended that investigations be conducted on the length/weight/sex by quarters of the two species to provide coverage of the suggested stocks and that studies on age and growth be conducted throughout the range of the species.

The need to determine estimates of interchange rates among the suggested and assumed stocks and the need to define spawning areas and seasons for both species, with particular emphasis on the south and eastern Pacific, were indicated.

II. STOCK STRUCTURE

Sailfish. Based on the distribution of larvae and longline catch rates, a possible two unit, western and eastern Pacific, stock structure for sailfish was suggested (Figure 1A).

Shortbill spearfish. On similar types of evidence, a two unit, northern and southern, stock structure for shortbill spearfish was proposed (Figure 1B).

III. POPULATION PARAMETERS

Sailfish. Kume and Joseph (1969) determined the following length-weight relation for eastern Pacific sailfish:

$$\log_{10} Y = -3.9357 + 2.4156 \log_{10} X,$$

and Wares and Sakagawa (1974) the following:

$$\log_{10} Y = -4.360 + 2.628 \log_{10} X,$$

where Y is weight in kilograms and X is eye-fork length in centimeters.

Skillman and Yong (1974) determined the length-weight relation for central Pacific sailfish as follows:

$$W = 2.0739 \times 10^{-5} L^{2.6054},$$

where W is weight in kilograms and L is snout-fork length in centimeters.

Other population parameters for sailfish are found in Table 2 of the Swordfish Rapporteur's Report.

Shortbill spearfish. Kume and Joseph (1969) determined the following length-weight relation for eastern Pacific shortbill spearfish:

$$\log_{10} Y = -6.8146 + 3.7242 \log_{10} X,$$

where Y is weight in kilograms and X is eye-fork length in centimeters.

Skillman and Yong (1974) determined the following length-weight relation for central Pacific sailfish:

$$W = 5.0083 \times 10^{-8} L^{3.8338},$$

where W is weight in kilograms and L is snout-fork length in centimeters.

No other population parameters for shortbill spearfish are available.

IV. STOCK ASSESSMENT

Because of problems with the basic longline data relative to species separation of sailfish and shortbill spearfish catches and unknown amounts of other species included in the sailfish/spearfish catch data, production

B. Effort Trends

Sailfish. Effective fishing effort in the Japanese longline fishery for sailfish was summarized for two areas: the western (Area 1) and eastern Pacific (Area 2) (Figure 3). Effective effort for sailfish in the western Pacific showed large fluctuations and no obvious trends. Effective effort was higher during the 1961-67 period than it was before and after that period. In the eastern Pacific, the effective effort did not increase substantially until 1965, then it peaked in 1968, and declined gradually through 1975.

Longline fishing in the Pacific is also conducted by vessels of Korea and Taiwan. This effort is principally in the south central and southwestern Pacific. The Taiwan nominal effort, which is centered in the southwestern and north central Pacific, appears to have peaked in 1973 to 54.7 million hooks and declined to 39.3 million hooks in 1976. The amount of effort expended by the harpoon, gill net, and recreational fisheries is unknown.

Shortbill spearfish. Longline effort data for shortbill spearfish north and south of the equator (see Figure 1B) were available in terms of nominal effort (Figure 4). In the northern area nominal fishing effort increased from 1952 through 1961 and fluctuated between about 180 million and 230 million hooks from 1962 to 1975. In the southern area, effort increased from 1952 through 1963, declined from 1964 through 1968, and has been stable since 1969.

C. Catch Rate Trends

Sailfish. The sailfish catch rate in the western Pacific (Area 1) fluctuated between about 6 and 14 fish/10,000 hooks from 1952 to 1959 and has been declining since 1959 (Figure 3). The average catch rate from 1960 to 1975 was about one-half of that during 1952-59. The sharp decline in 1975 may be partially the result of deep fishing for bigeye tuna, a method which is less effective for sailfish, which tend to inhabit the upper layers of the ocean.

In the eastern Pacific (Area 2) there were large fluctuations in a generally rising trend of catch rates from 1959 to 1965; subsequently the catch rate has fluctuated less on a downward trend (Figure 3). The 1975 catch rate is approximately two-thirds of that observed during the high catch rate period of 1964 to 1968.

Shortbill spearfish. Because shortbill spearfish and sailfish catches are pooled in the catch statistics, shortbill spearfish catches were estimated by using historical sailfish to shortbill spearfish catch ratio data; the catch rate is based on nominal effort (Figure 4). The catch rate for shortbill spearfish in the northern area increased from a level of 4 fish/100,000 hooks during the period 1952 through 1961, to an average of about 8 fish/100,000 hooks in recent years. The southern area annual catch rate shows a smaller increase, from about 20 fish/100,000 hooks during the period 1952 through 1962, to about 30 fish/100,000 hooks since 1962, a much better (by a factor of 4) catch rate than in the northern area.

SAILFISH, ISTIOPHORUS PLATYPTERUS, AND SHORTBILL SPEARFISH,
TETRAPTURUS ANGUSTIROSTRIS

James L. Squire and Ziro Suzuki

I. REVIEW OF FISHERIES DATA

Sailfish, Istiophorus platypterus, are widely distributed in the Pacific but they are generally regarded as a species common to waters near continental or island areas. Their latitudinal limits in the Pacific appear to extend from lat. 40°-45°N to about lat. 40°S (Figure 1A).

Shortbill spearfish, Tetrapturus angustirostris, are widely distributed in tropical and temperate offshore waters of the central Pacific and their distributional limits are similar to that of sailfish (Figure 1A). However, relatively small numbers of this species are taken on tuna longlines. Because the two species are often combined in the longline catch statistics, the distributional chart, which is based on longline catches, should be considered tentative.

The major fishery for sailfish and shortbill spearfish is the commercial longline fishery conducted principally by Japan, Republic of China (Taiwan), and Republic of Korea, which accounts for about 90% of the Pacific catch of these species. Important areas of sailfish catches on longlines are in the eastern Pacific to approximately 600 miles offshore from North America and in the western Pacific from off northeast Australia, New Guinea, and from the Philippine Islands to the southern islands of Japan. In the western Pacific, this species has been taken for several decades incidentally to tunas on longlines; in the eastern Pacific, substantial fishing effort was not applied until about 1965. Catches of sailfish are also made by harpoons and gill nets, and there is a recreational fishery in the eastern Pacific, off central Mexico to Ecuador. In the western Pacific, sailfish are taken primarily in the Coral Sea around New Guinea and in the East China Sea.

One of the shortcomings of the sailfish and shortbill spearfish data is that catches of both species are combined in the catch statistics, and determining the exact catch of each species is difficult. Also, catch data by species are not available for the Korean and Taiwanese fisheries. An additional problem is that some other incidentally caught species may be reported by fishing vessels in the sailfish/spearfish group.

A. Catch Trends

Before 1964 the annual Pacific landings of sailfish and shortbill spearfish amounted to less than 8,000 metric tons (MT) (Table 1; Figure 2). A marked increase in catch to 12,800 MT was recorded in 1965. During the remainder of the 1960's, the catches continued at around the 12,000 MT level and thereafter declined to about 5,500 MT in 1975. The actual catches of sailfish and shortbill spearfish are probably lower than reported because totals include catches of species other than sailfish or shortbill spearfish.

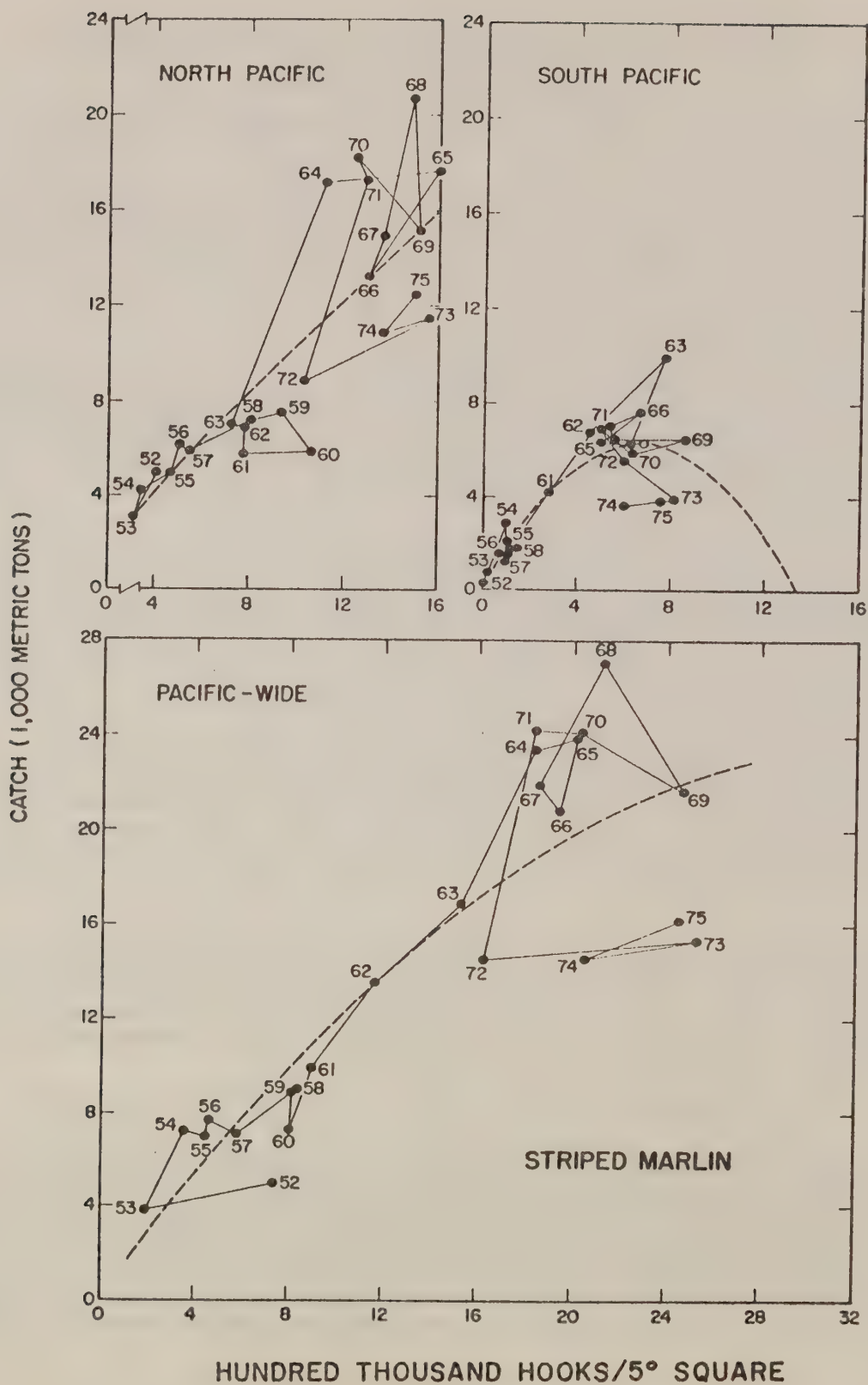


Figure 4.--Production models for hypothesized striped marlin stocks in the Pacific.

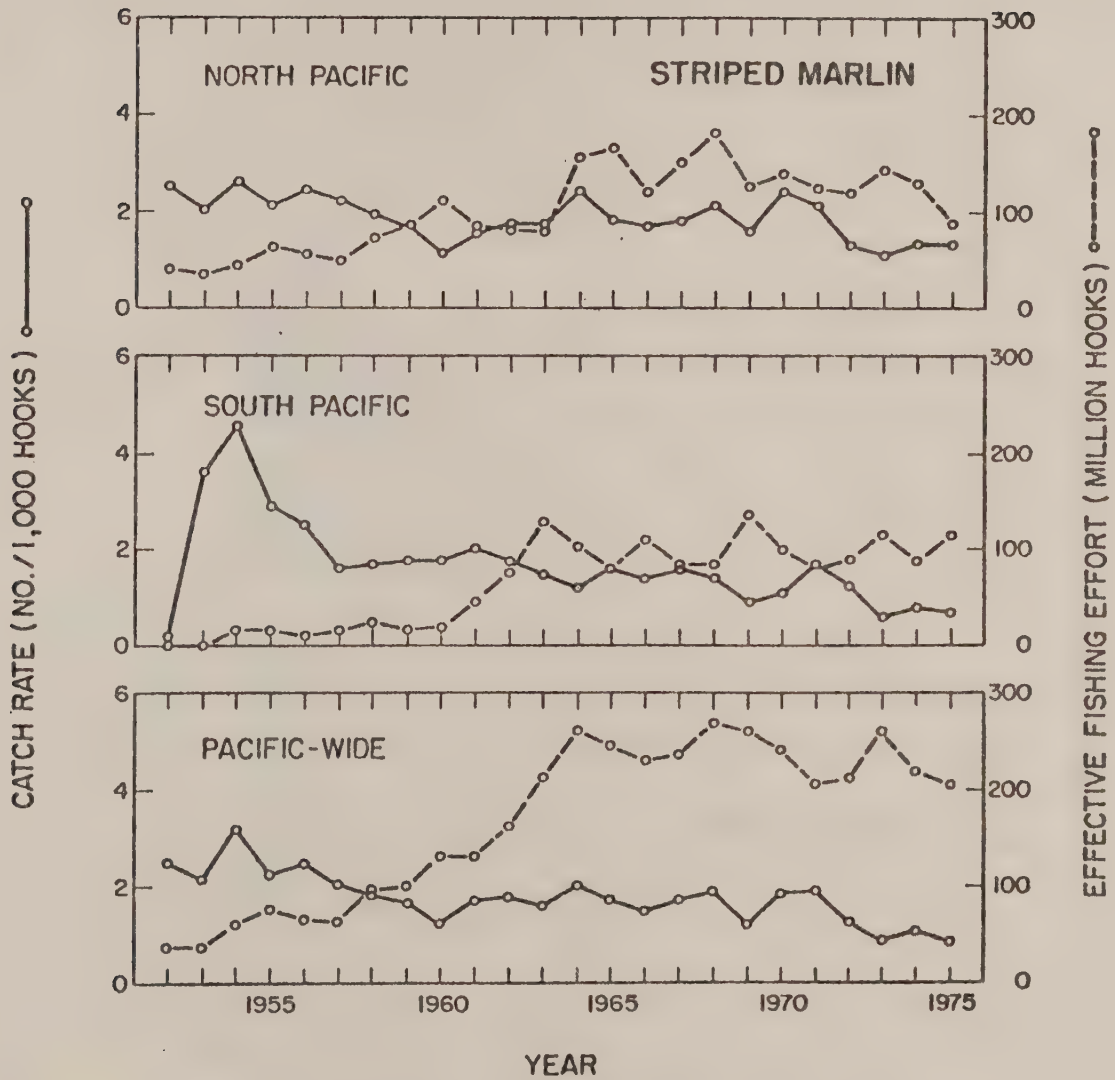


Figure 3.--Catch rates and effective fishing effort for striped marlin in the Pacific.

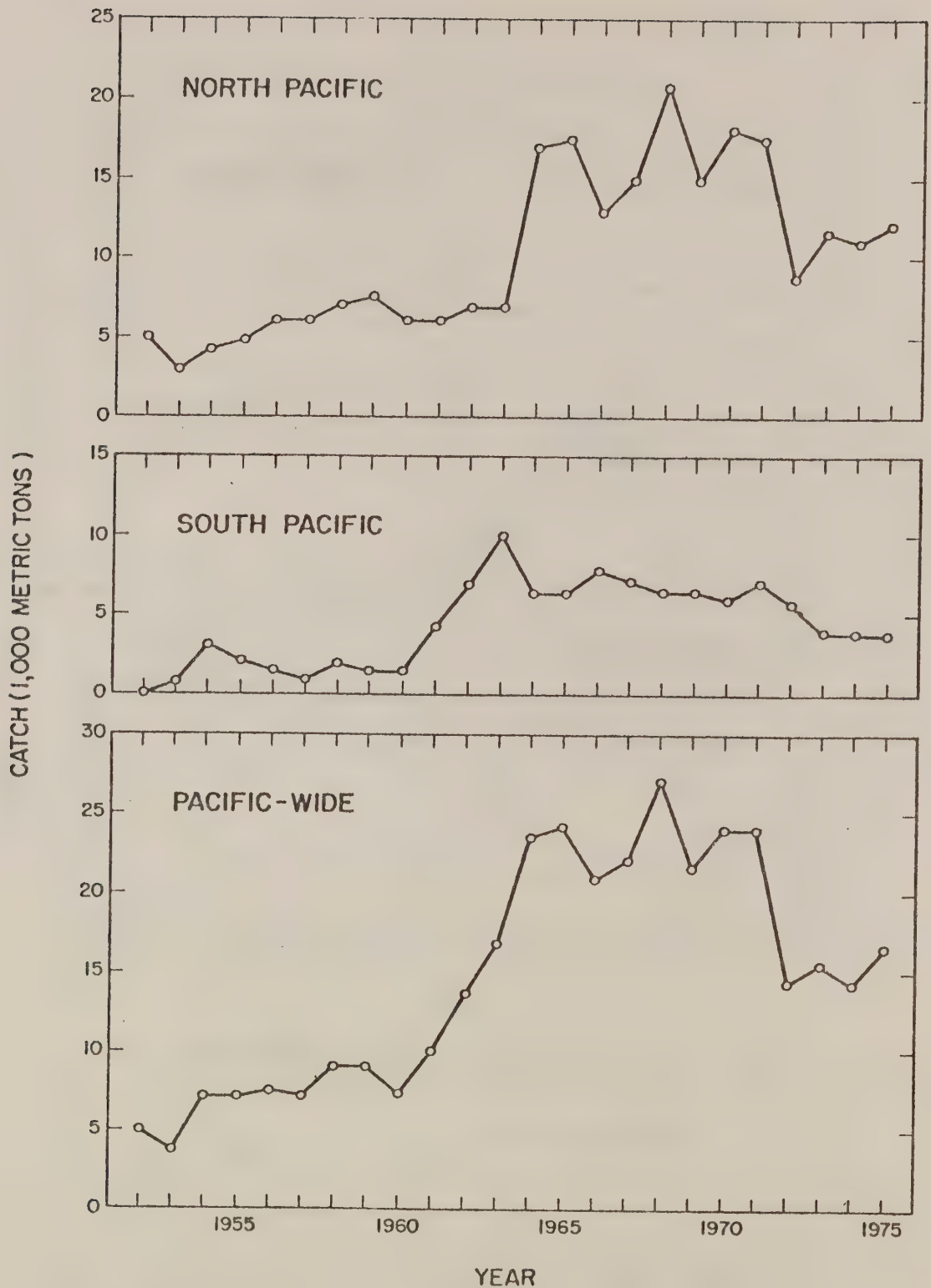


Figure 2.--Catches of striped marlin in the Pacific, 1952-75.

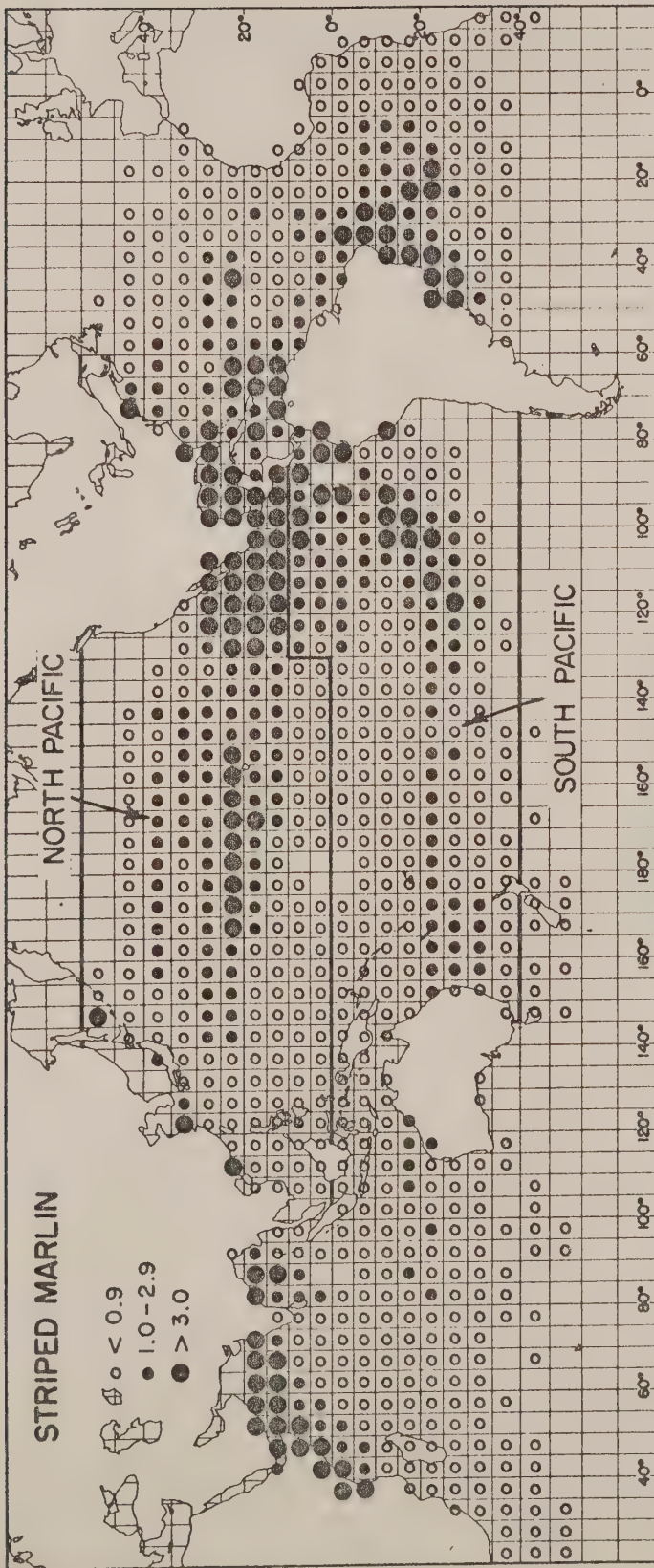


Figure 1.--Distribution of striped marlin in the Pacific. The circles indicate mean catch rates (number of fish/1,000 hooks). Also shown are the boundaries of the hypothesized stocks.

Table 1.--Striped marlin catches (metric tons) by countries in the Pacific Ocean.

Year	Japan	Korea	Taiwan	United States	Total
1952	4,992				4,992
1953	3,789				3,789
1954	7,208		48		7,256
1955	6,927		148		7,075
1956	7,526		198		7,724
1957	6,944		206		7,150
1958	8,788		128	83	8,999
1959	8,803		108	75	8,986
1960	7,242		58	62	7,362
1961	9,922		104	58	10,084
1962	13,359		242	84	13,685
1963	16,347		500	97	16,944
1964	22,893		500	87	23,480
1965	19,830		4,100	87	24,017
1966	16,410	70	4,400	87	20,967
1967	18,109	143	3,711	87	22,050
1968	22,103	93	4,766	181	27,143
1969	16,813	159	4,589	145	21,706
1970	19,564	164	4,335	158	24,221
1971	19,099	164	4,923	78	24,264
1972	13,344	164	961	72	14,541
1973	14,122	164	1,079	42	15,407
1974	13,641	164	825	39	14,669
1975	15,254	164	812	49	16,279

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at the equator. Larval distribution suggests two centers of spawning, one in the north and one in the south, although gonad index data (Kume and Joseph 1969) suggest that spawning occurs throughout the eastern tropical Pacific, the supposed region of stock mixing.

III. POPULATION PARAMETERS

Few studies have concentrated on quantifying critical population parameters of striped marlin. Most published estimates are preliminary and need refinement.

Eldridge and Wares (1974) estimated that Pacific striped marlin reach sexual maturity between 140 and 165 cm and has a single mid-summer spawning period. Fecundity is in the order of 11.3×10^6 to 28.6×10^6 eggs for females 155 to 180 cm. Skillman and Yong (1974, 1976) reported length-weight relations and an age-length relation for the Pacific striped marlin. The length-weight relation, sexes combined is

$$W = (5.7126 \times 10^{-7}) L^{3.3756}$$

where W = weight in kilograms and L = total length in centimeters. Estimates of other population parameters are given in Table 2 of the Swordfish Rapporteur's Report.

It must be noted that with the exception of the growth curves, which still need to be verified, the other population parameters should be considered preliminary and serve only to indicate possible orders of magnitude.

IV. STOCK ASSESSMENT

Very little data on the fisheries and population dynamics of striped marlin including reliable estimates of population parameters and size composition data, are available. Total catch figures are available, although in some instances the catch estimates are based on marginal sample data. The Japanese longline fishery has provided the longest time series of catch and effort data. Because of this lack of reliable data, a simple approach was used in assessing the state of the Pacific striped marlin stocks which consisted of the determination of trends in longline catch rate and effort and the use of production model analysis.

The results of the production model analysis should be interpreted cautiously, however, as it relies on the basic assumptions that (1) the model is applied to a unit stock, (2) equilibrium conditions apply to the stock, and (3) the age-groups being fished have remained and will continue to remain the same. These assumptions have not been adequately verified for striped marlin.

A. Northern Stock

The production model estimated a maximum sustainable yield (MSY) of about 70,000 MT produced by an optimum effective effort of about 13.2 million hooks/5° square for striped marlin in the North Pacific (Figure 4). This estimate of optimum effective effort is beyond the range experienced by the fishery

In the southwestern region (Area 2), the longline catches showed a gradually increasing trend (Figure 5); the catch rates fluctuated between 2 fish/10,000 hooks and 3 fish/10,000 hooks during the period 1952-67 (Figure 6). The rate then increased to the current high level of 4 fish/10,000 hooks.

Longline catches in the eastern Pacific (Area 3) showed an increasing trend after 1960, following a period of small catches from 1952 to 1960 (Figure 5); the catch rates gradually increased from about 2 fish/10,000 hooks in 1954 to 6 fish/10,000 hooks in 1968 (Figure 6). In 1969 and 1970 the catch rates increased sharply to a record high of about 11 fish/10,000 hooks before declining to a level of about 6 fish/10,000 hooks in 1971-75.

V. OVERALL STOCK APPRAISAL

The swordfish stocks of the Pacific Ocean appear to be healthy and capable of sustaining increased yields with increased effort. However, should the longline fishery resort to night fishing as was the standard method of fishing in some areas prior to the mid-1960's, then the greater efficiency of the gear could result in the catch exceeding the MSY with about a 25% increase in the current levels of fishing effort.

VI. RECOMMENDATIONS

A. Statistics

Longlining for swordfish is most effective during the night, whereas, longlining for tunas is most effective during the day. Prior to the mid-1960's, longlining in the more productive swordfish areas, especially in the northwestern Pacific, was conducted during the night. Since then this practice has decreased as the fishery has been targeting the higher priced tunas.

This change in fishing practice has complicated the longline statistics which are used to measure apparent abundance of swordfish. Published statistics currently do not identify type of fishing, i.e., night and day operations, and more precise stock assessments based on the longline data will require separation of the data. The participants, therefore, recommended that the longline catch-effort statistics be separated into type (day and night) of operations.

The participants also recommended that size and sex data be collected from all fisheries, and catch-and-effort data be collected from the surface fisheries. These data are essential for using more sophisticated assessment techniques and for obtaining more precise management advice.

B. Research

Information on stock structure of a fish population is important for proper management of the resource. For Pacific swordfish, the stock structure is not clearly known although available data suggest that the population might consist of a single Pacific-wide stock or possibly, three separate stocks.

Available techniques for stock identification are expensive to apply and not entirely reliable in producing clear results. The participants therefore recommended that different stock structure hypotheses be tested using existing fisheries data to determine their impact on assessments before any major program for stock identification of swordfish is considered.

The key to more precise stock assessments for swordfish is more reliable information on stock densities and better estimates of population dynamics parameters. The participants recommended that methods of aging swordfish receive more research attention since this is important for estimating population dynamics parameters.

C. Management

With current levels of fishing effort (about 1.8 million hooks/5° square) and longline fishing predominantly during the day, the swordfish stocks are not being exploited beyond the estimated MSY of about 20,000 MT for the Pacific-wide stock. However, the fishery should be monitored closely for changes in the mode of operation, especially changes to night fishing, which could result in the stocks being exploited beyond MSY.

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Table 1.--Swordfish catches (metric tons) by countries for the Pacific Ocean.

Year	Japan	Taiwan	Korea	United States	Chile	Peru	Others	Total
1952	11,182			157				11,339
1953	11,604			85				11,689
1954	13,301	77		14				13,392
1955	16,220	185		80				16,485
1956	12,167	254		163				12,584
1957	15,771	250		222				16,243
1958	20,815	247		279				21,341
1959	19,136	262		265				19,663
1960	22,944	273		192				23,409
1961	23,636	432		218				24,286
1962	14,037	544		23				14,604
1963	13,775	300		58				14,133
1964	9,703	300		109				10,112
1965	11,955	300		194	200	300		12,949
1966	13,283	600	41	277	200	200		14,601
1967	13,083	838	47	181	200	1,300		15,649
1968	12,983	974	55	118	200	800	100	15,230
1969	15,612	1,023	89	610	300	1,200	100	18,934
1970	11,301	1,053	115	558	200	2,400	100	15,727
1971	9,182	1,149	115	91	200	200	100	11,037
1972	8,846	1,111	115	157	100	600	100	11,029
1973	9,644	1,269	115	363	400	1,900	100	13,791
1974	9,517	1,157	115	384	218	270	3	11,664
1975	11,274	1,099	115	512	218	158		13,376

Table 2.—Summary of estimates of some population parameters for billfishes. Growth parameters are for the von Bertalanffy growth equation and mortality rates are for the coefficient of instantaneous total mortality (Z) and coefficient of instantaneous natural mortality (M).

Species and locality	Growth parameter			Mortality rate		
	K	t ₀ (yr)	L _∞	Size range (cm)	Z	M
Sailfish, Atlantic	0.901		95.55 in. (243 cm)		1.73	Based on data from de Sylva (1957)
Sailfish, Pacific	0.472		232 cm	¹ 130-210	0.90	Based on data from Koto and Kodama (1962a)
Sailfish, Atlantic	0.289		248 cm		0.54	Based on data from Jolley (1977)
Swordfish, Atlantic	0.230		365 cm	60-279	0.12-0.65	Caddy (1977)
Swordfish, Pacific	0.124		309 cm	¹ 61-245		Estimates of K based on data from Yabe et al. (1959); L _∞ estimated by Yabe et al. (1959)
White marlin, Atlantic					0.35±0.10	Mather et al. (1974)
Blue marlin, Pacific						
Male	0.285-0.815	0.106	282-371 cm	100-280	0.53-1.56 } 0.15-0.21 }	K, t ₀ , and L _∞ estimated by Skillman and Yong (1976); estimates of M based on data from Skillman and Yong (1976)
Female	0.123-0.175	-0.202	540-626 cm	50-400		
Striped marlin, Pacific	0.264		¹ 275	¹ 120-235		Based on data from Koto (1963)
Male	0.315-0.417	-0.521	277.4-314.4 cm		1.94	Estimates of K, t ₀ , and L _∞ by Skillman and Yong (1976).
Female	0.696-0.709	0.136	251.0-251.8 cm		1.38	Estimates of M based on data from Skillman and Yong (1976). Estimate of Z based on data from Skillman and Yong (1976) and Yoshida (1974)
Black marlin, Pacific	0.474		¹ 282	¹ 150-250		Based on data from Koto and Kodama (1962b)

¹ Eye-fork length.

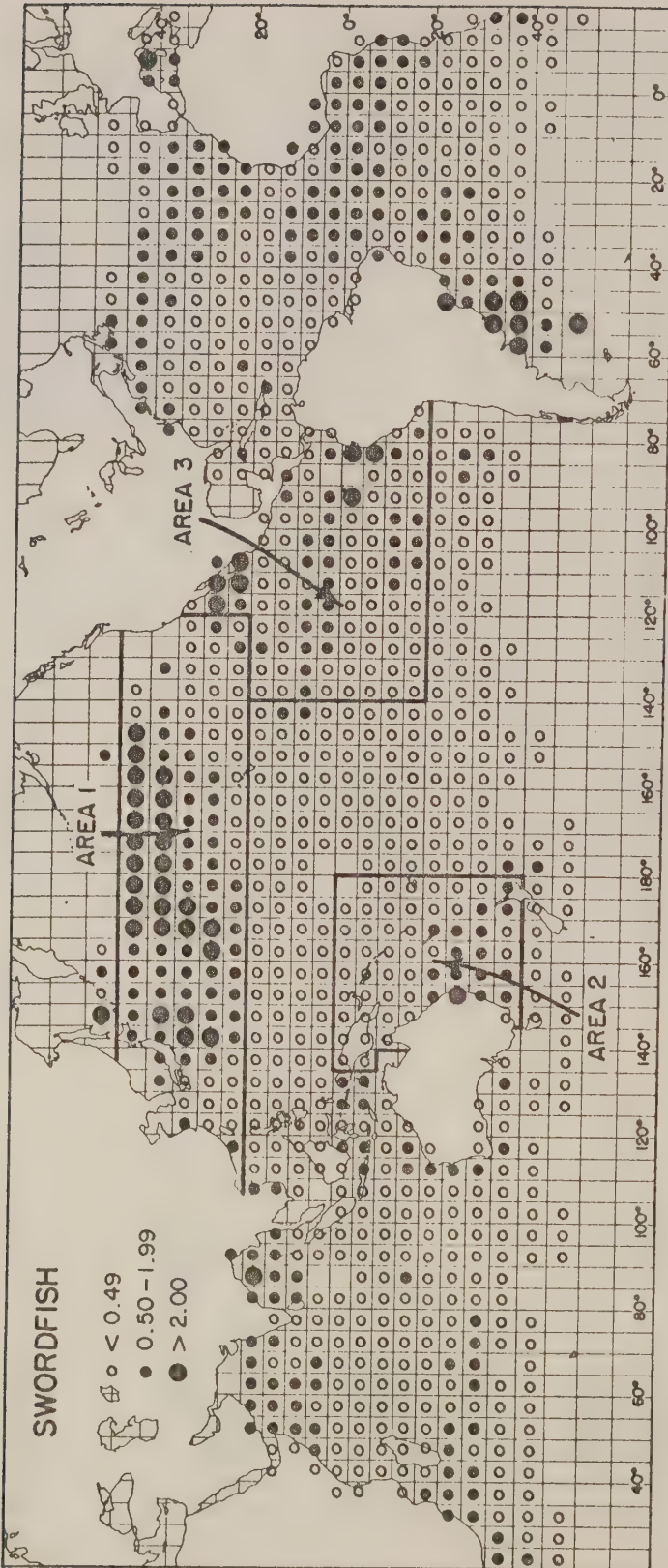


Figure 1.--Distribution of swordfish in the Pacific. The circles indicate mean catch rates (number of fish/1,000 hooks). Also shown are centers of concentration of hypothesized swordfish stocks in the Pacific.

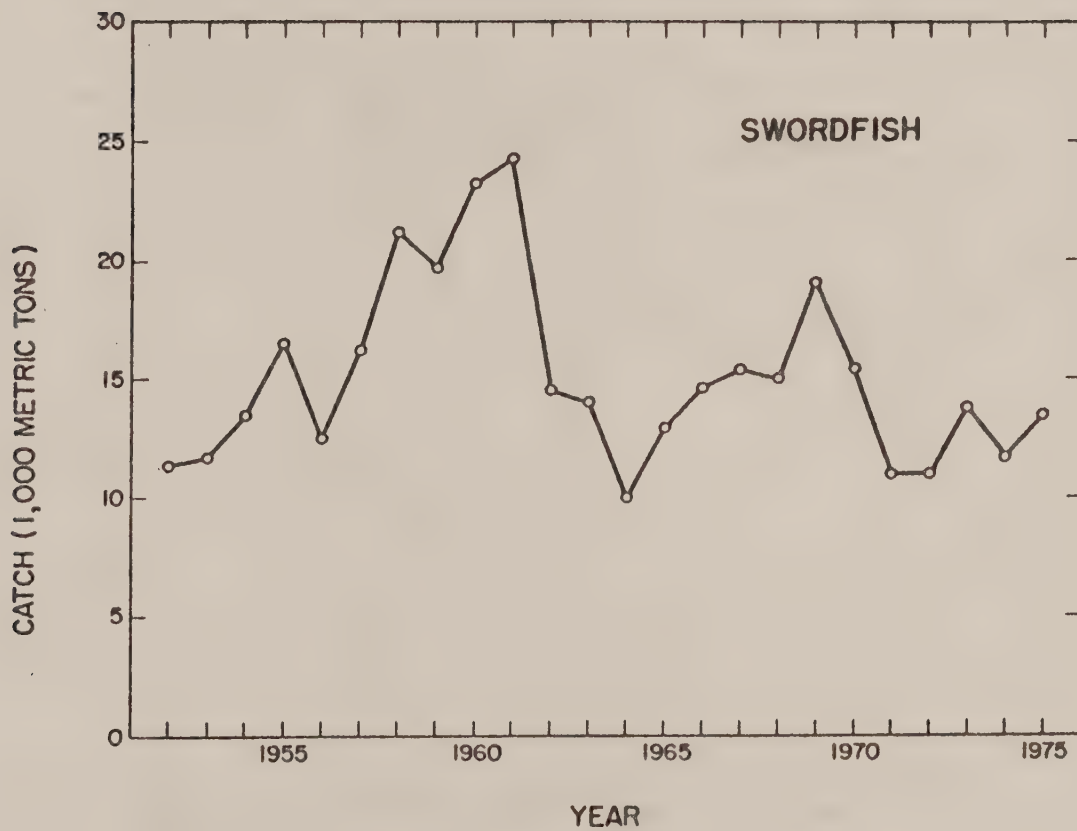


Figure 2.--Total catch of swordfish in the Pacific
(Suzuki and Honma BSAW/WP4).

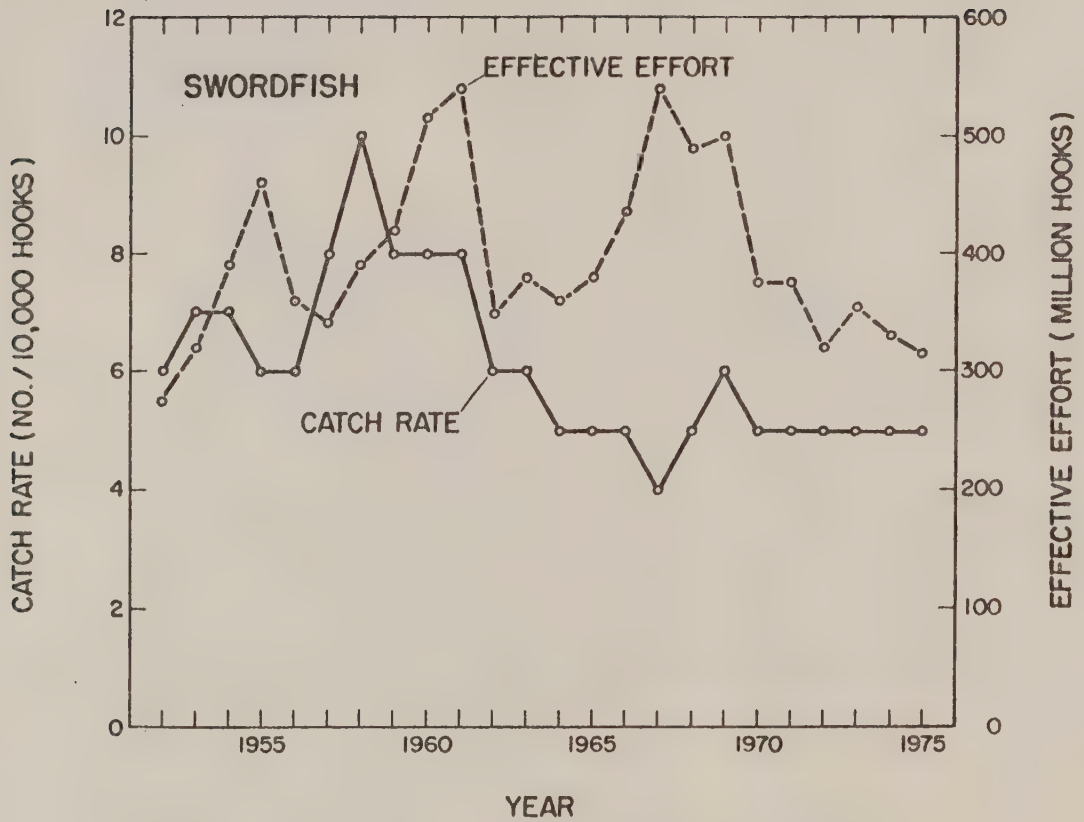


Figure 3.--Pacific-wide catch rate and effective fishing effort for swordfish (Suzuki and Honma BSAW/WP4).

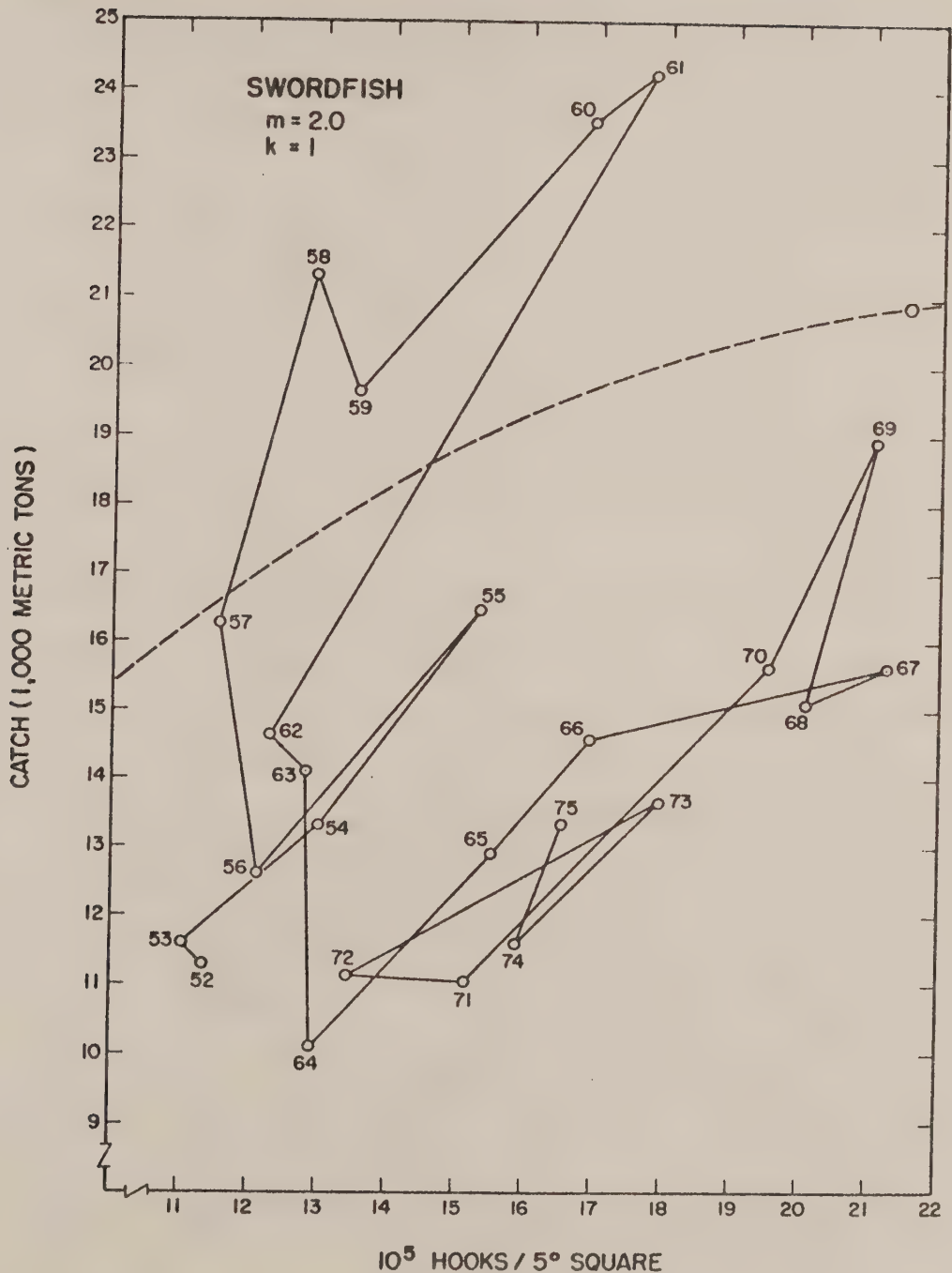


Figure 4.--Relationship of catch of swordfish and effective fishing effort. The equilibrium yield curve (Schaefer production model) is shown for data for 1952-63 only.

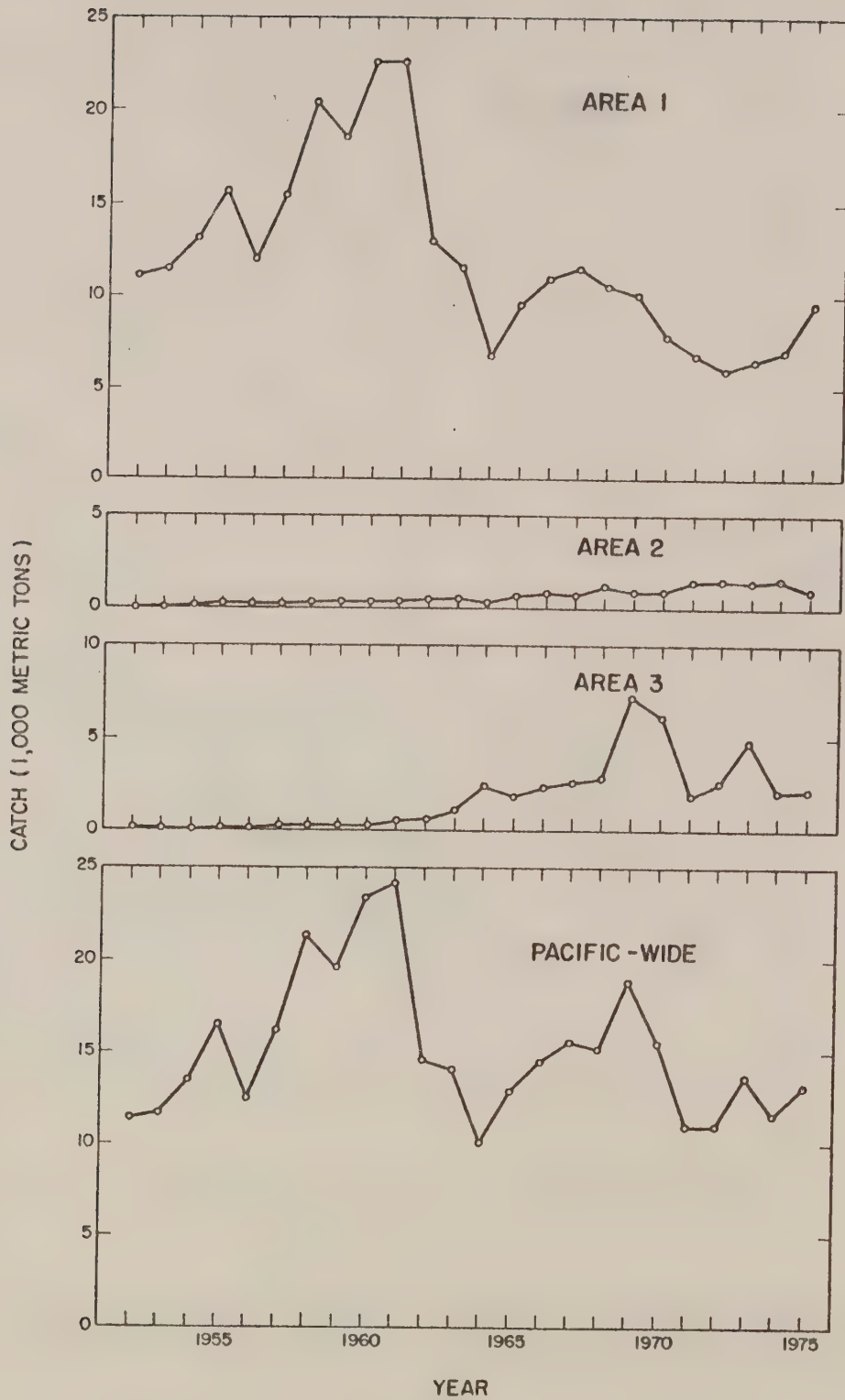


Figure 5.--Swordfish catch in the Pacific Ocean
(Suzuki and Honma BSAW/WP4).

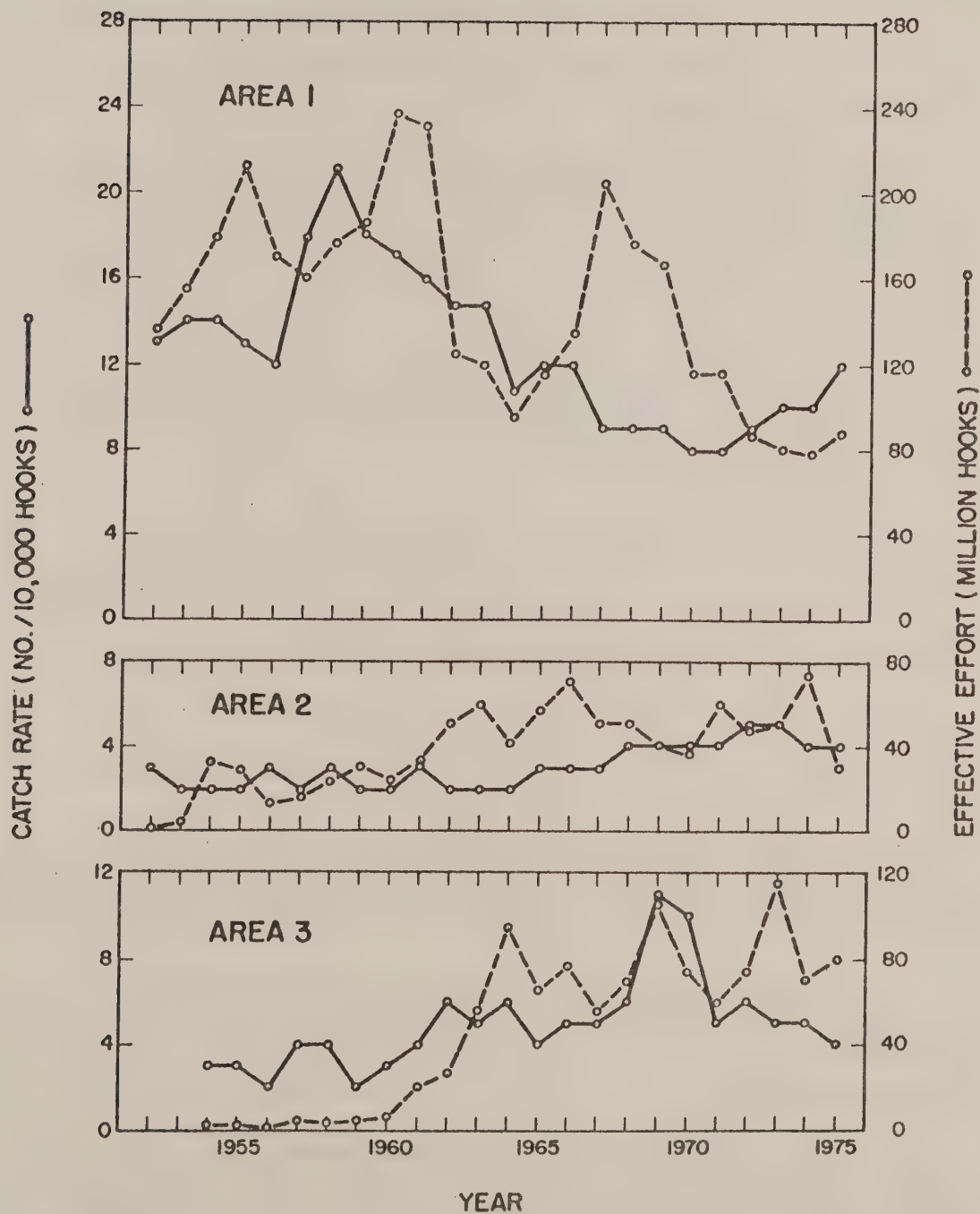


Figure 6.--Catch rates and effective fishing effort for swordfish in the Pacific.

BLACK MARLIN, MAKAIRA INDICA

Jerry A. Wetherall and Rong-Tszong Yang

I. REVIEW OF FISHERIES DATA

Black marlin, Makaira indica, occur across the entire Pacific Ocean between about lat. 45°N and 50°S. Their latitudinal distribution is somewhat more restricted in the eastern than in the western Pacific (Figure 1). Catch rates in the tuna longline fisheries show that the density of black marlin is generally very low except in certain coastal waters. In the western Pacific, seasonal concentrations of this species are seen in such areas as the East China Sea and the Coral Sea. The Coral Sea is assumed to include spawning areas for black marlin as evidenced by gonad condition and larval occurrence. In the eastern Pacific, high densities are observed in the coastal waters of Panama and Ecuador. In the mid-Pacific region, occurrence of black marlin is highest in the vicinity of islands.

A. Catch Trends

The total catch of black marlin in the Pacific rose to a peak of about 6,500 metric tons (MT) in 1956, then dipped to about 3,000 MT in 1959 and fluctuated between about 2,000 and 4,000 MT from 1960 to 1975 (Table 1; Figure 2). There are uncertainties in the estimates of black marlin catches in the Pacific; it is believed that some catches are unreported.

Most of the black marlin catches in the northwestern Pacific are made by Republic of China (Taiwan) commercial fishermen using mostly tuna longlines on short-range vessels under 50 MT, or using harpoons. Catches made by Japanese tuna longliners in the area are relatively minor.

In the southwestern Pacific, most of the black marlin catches are made by Japanese tuna longliners and lesser amounts are taken by Taiwanese and Republic of Korea vessels. There is also an active recreational fishery for black marlin primarily off Cairns, Australia.

A recreational fishery accounts for some of the catch of black marlin in the eastern Pacific but almost all the catch in this area is made by Japanese longliners.

B. Effort Trends

Effort data have been summarized for four areas in the Pacific, northwestern (Area 1), southwestern (Area 2), eastern (Area 3), and western (Area 4) (Figure 3), where black marlin are relatively densely distributed. Black marlin occupying these areas may represent separate stocks. Because total catch figures are used to estimate effective fishing effort, these estimates are biased to the same extent as the corresponding catch estimates.

Effective fishing effort from 1952 to 1975 has been erratic and does not show any discernible trends in Areas 1, 2, and 4. In the eastern Pacific (Area 3), where the Japanese tuna fishery commenced in 1956, the effective fishing effort has been on a generally increasing trend.

C. Catch Rate Trends

In the northwestern Pacific (Area 1), the catch rate reached a peak in 1954 and declined to its lowest level in 1975. In the southwestern Pacific (Area 2), the catch rate reached a peak early in the development of the fishery in 1955, declined to less than 4 fish/10,000 hooks in 1957 and fluctuated between about 1 and 3 fish/10,000 hooks from 1958 through 1975. The catch rate in the eastern Pacific (Area 3) reached a peak in 1957 and declined thereafter. The western Pacific (Area 4) catch rate reflects the same trends as that in the constituent areas (Areas 1 and 2).

II. STOCK STRUCTURE

The stock structure of black marlin in the Pacific is not clear; however, their restricted coastal distribution and the presence of isolated high catch-rate areas suggest the possible existence of more than one stock in the Pacific. It has been suggested that there may be two or three stocks: one in the eastern Pacific and one or two in the western Pacific (Figure 1). The situation is complicated by the strong possibility of mixing between black marlin in the Indian Ocean and the western Pacific.

III. POPULATION PARAMETERS

Owing to a lack of black marlin age data, no estimates of mortality have been made. Estimates of K and L_{∞} (von Bertalanffy growth parameters) for black marlin are found in Table 2 of the Swordfish Rapporteur's Report.

IV. STOCK ASSESSMENT

Because of our uncertainty in total catch figures and stock structure, no attempt was made to fit production models or to estimate maximum sustainable yield (MSY) for black marlin in any area in the Pacific. The consensus of the participants was that a reliable production model analysis will require a better accounting of catches.

V. OVERALL STOCK APPRAISAL

While no definitive assessments of black marlin stocks are yet available, the substantial decline in catch rates from the early 1950's to 1975 suggests that a very large increase in total catch over recent levels is probably not sustainable.

VI. RECOMMENDATIONS

A. Statistics

For improved stock assessments of black marlin, it is essential that complete catch and nominal effort statistics be made available from all harvesting nations, especially Republic of China (Taiwan), Republic of Korea, and Japan. In addition, statistics on total catch and effort should be gathered systematically from recreational fisheries, particularly off northwest Australia.

Thorough stock assessments will require extensive data on the size composition of black marlin catches in commercial and recreational fisheries. These statistics should be acquired over all time-area strata.

B. Research

Continued research is required to evaluate the status of black marlin stocks. Attention must be paid to improve understanding of stock structure, to better estimate total catches, and to validate the stock density measures.

In view of the importance of population structure to proper stock assessment, the tagging programs currently underway should be maintained.

Finally, concerted efforts are needed to determine the age of black marlin and to establish age-size relationships.

C. Management

Because no MSY estimates are available, it is presently not useful to make any management recommendations with respect to catch or effort limitations. However, future analyses may show that catches of black marlin presently exceed MSY in some stocks, and that restraints should be considered. In any case, effective management will depend on a much improved understanding of stock structure and stock dynamics.

Table 1.--Black marlin catches (metric tons) by countries in the Pacific Ocean.

Year	Japan	Taiwan	Korea	Total
1952	1,806			1,806
1953	3,188			3,188
1954	4,713	657		5,370
1955	3,690	1,689		5,379
1956	4,443	2,023		6,466
1957	5,107	1,269		6,376
1958	2,581	1,967		4,548
1959	1,905	1,176		3,081
1960	1,938	783		2,721
1961	2,312	858		3,170
1962	2,852	1,214		4,066
1963	2,580	600		3,180
1964	2,205	600		2,805
1965	3,439	600		4,039
1966	3,225	400	104	3,729
1967	2,034	648	154	2,836
1968	1,588	661	113	2,362
1969	2,053	343	150	2,546
1970	1,644	453	110	2,207
1971	1,773	791	110	2,674
1972	1,424	1,890	110	3,424
1973	1,614	1,996	110	3,720
1974	1,175	1,763	110	3,048
1975	962	1,724	110	2,796

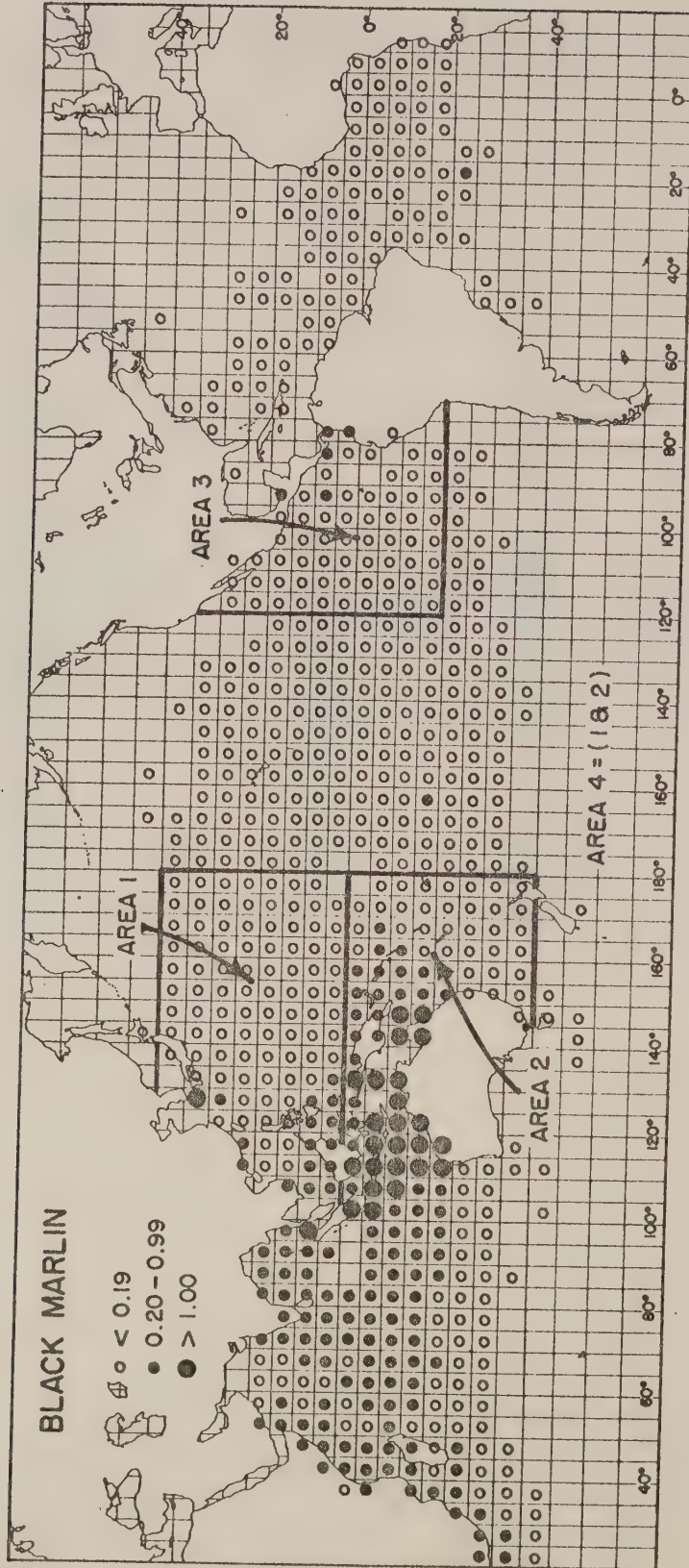


Figure 1.--Distribution of black marlin in the Pacific Ocean. The circles indicate mean catch rates (number of fish/1,000 hooks). Also shown are the boundaries of suggested black marlin stocks.

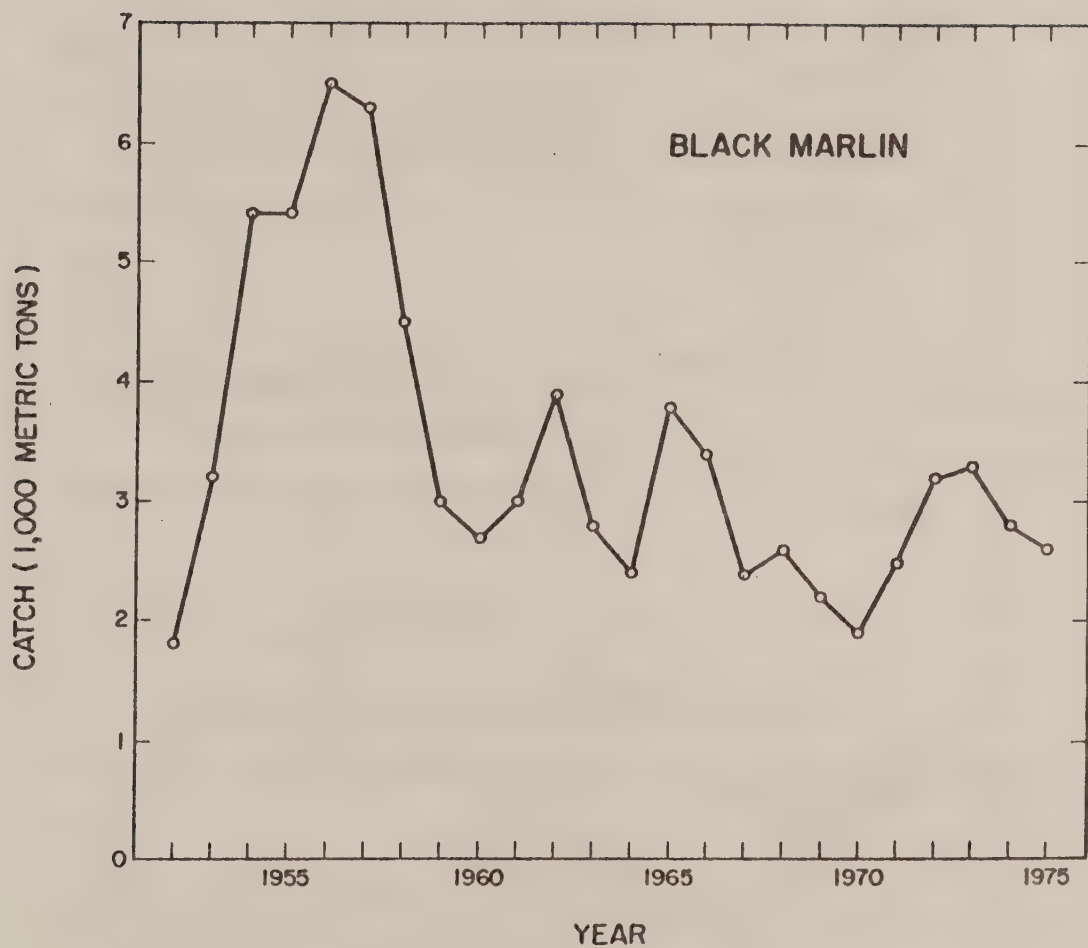


Figure 2.--Total catch of black marlin in the Pacific.

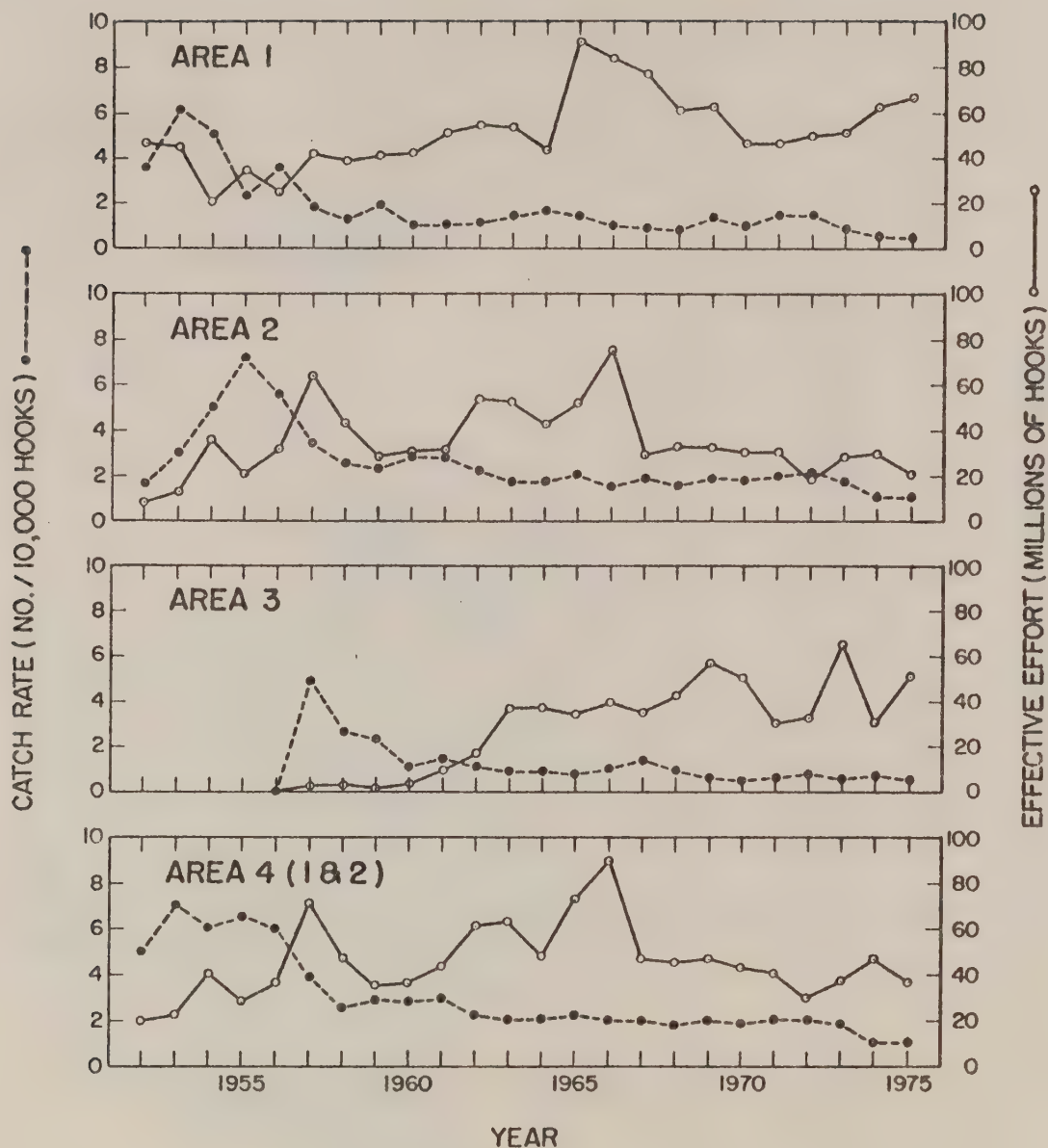


Figure 3.--Catch rates and effective fishing effort for black marlin in the Pacific.

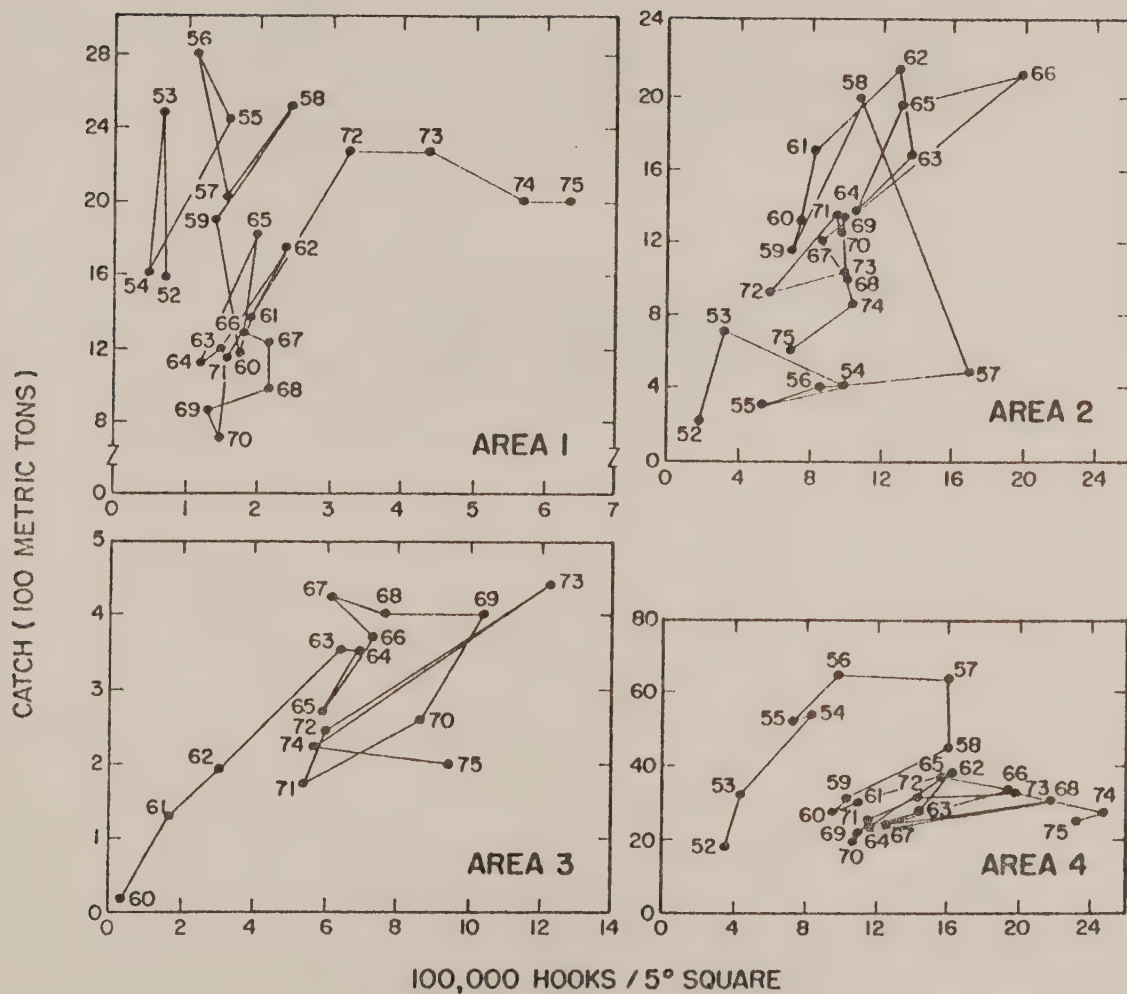


Figure 4.--Relation between catch and effective effort for black marlin in four areas in the Pacific.

DESCRIPTIVE STATISTICS ON THE SIZE COMPOSITION
OF SKIPJACK TUNA, KATSUWONUS PELAMIS, LANDED IN THE
HAWAIIAN POLE-AND-LINE FISHERY, 1946-77

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Prepared for
Indo-Pacific Fishery Commission
Eighteenth Session and Symposium
Manila, Philippines
8-17 March 1978

February 1978

This is a draft working paper prepared solely for discussions at the Eighteenth Session and Symposium of the Indo-Pacific Fishery Commission. It is not intended for publication in its present form and should not be cited.

INTRODUCTION

The Hawaiian skipjack tuna, Katsuwonus pelamis, fishery is a pole-and-line or live-bait fishery that is carried out usually within 90 nautical miles (167 km) of the main islands. The fishing boats, or aku sampans, range from 27 to 77 gross tons or 18 to 25 m in length and are generally constructed of wood (Uchida 1966). The landings by the skipjack tuna fleet have varied from 2,700 to 7,300 metric tons (MT) with a mean of about 4,100 MT.

The size composition of the skipjack tuna landings varies seasonally and annually. Fish as small as 30 and as large as 89 cm fork length (FL) are commonly caught. It has been noted that two modal size groups, at 45 and 70 cm FL, are commonly present in the summer. The 70 cm FL group makes up the "season" fish that contributes to the large catches during the summer. As many as three modal size groups, at 35, 50, and 70 cm FL, are sometimes evident during the winter (Rothschild 1965). There are no size restrictions placed on the fishery by the State of Hawaii, the local cannery, nor any of the fresh fish marketing outlets. While there is a market demand for skipjack tuna for all sizes landed, the cannery as well as the fresh fish market prefer fish as large as possible.

Basic Statistics on Length

Fork length statistics are available for analysis from September 1946 through December 1954 and from August 1959 through June 1977, although not for every month. Sampling of the landings at the local cannery is continuing. Certain basic statistics, including the mean, minimum, and maximum, have been calculated on a monthly, quarterly, and yearly basis and are presented here for quarters and years (Table 1).

There is no evidence of a long-term trend in the mean, minimum, or maximum statistics for the history of the fishery (Figure 1). Over the 28 years of the time series, the means of the mean, minimum, and maximum statistics are 60.4, 33.4, and 86.1 cm FL, respectively. The smallest fish measured was 30 cm FL, and the largest was 89 cm FL. These minimum and maximum values occurred in several of the months in different years in the time series.

On a quarterly basis averaged over all 28 years, there are recognizable intrayear trends in the data. The means of the quarterly mean and maximum statistics start at low values in the first quarter and rise to a peak in the third quarter (Figure 2). In the Hawaiian fishery, skipjack tuna landings also reach a peak in the third quarter. The minimum statistic follows a different pattern with the peak occurring in the fourth quarter.

Within the third quarter, the mean of the monthly mean fork length statistics reaches a peak in July whereas the means of the minimum and maximum statistics increase slightly from June through August (Figure 3).

Size-Frequency Distributions

While the basic statistics given in the previous section indicated that length composition of the landings varies both within and between years, these statistics do not provide any information on the length-group (or modal group) composition and its variability. In this section, we present length-frequency distributions for 4 cm FL groups by quarters and months for selected years. Modal groups, which are indicated by arrows in the figures, were selected visually, not by using any statistical procedure. The 4 cm FL grouping is probably too large to follow growth or progression of modes in any but the youngest length-groups.

The quarterly histograms for 1952, 1962, 1972, and 1976 (Figure 4) most clearly show the seasonal variability in the modal group composition of the landings. The third quarter contained only two length-groups (usually 46-49 cm and 70-73 cm FL) in all but 1 year. The exception (1976) contained three length-groups. The second quarter sometimes looks like a summer quarter with two modal groups and sometimes like a winter quarter with up to four modal groups. In the third quarter as few as one length group and as many as three can be seen. The fourth quarter is equally variable, but the maximum number of modal groups reaches four.

Monthly histograms for 1974-77 are presented in Figure 5. The monthly data, of course, shows more variability than the quarterly data and suggest that if the data must be grouped into quarters, these quarters might better be December-January-February, March-April-May, June-July-August, and September-October-November. While it is possible to follow some modal groups from month to month, there is no consistent indication of growth nor is the percent contribution of a given modal group consistent.

Going beyond these simple descriptors of the length statistics for the Hawaiian fishery, we are now attempting to statistically separate length-groups using a modification of a normal distribution separator algorithm written by Yong and Skillman (1975) and used recently by Skillman and Yong (1976).

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Table 1.--Quarterly and yearly fork length (in centimeters) statistics for skipjack tuna from the Hawaiian pole-and-line fishery.

Year	Quarter 1			Quarter 2			Quarter 3			Quarter 4			Year		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
1946	--	--	--	--	--	--	60.9	39	86	63.9	39	86	62.4	39	86
1947	57.6	38	85	49.0	31	84	58.1	33	85	--	--	--	54.6	31	85
1948	55.8	34	89	45.7	35	83	58.1	34	85	59.4	40	83	51.7	34	89
1949	56.6	50	68	71.7	33	84	63.8	37	85	54.3	40	79	66.5	33	85
1950	55.0	37	81	53.7	34	84	60.3	41	83	64.7	41	81	58.0	34	84
1951	64.2	49	80	62.7	31	81	63.7	36	82	50.4	40	75	61.3	31	82
1952	--	--	--	52.5	33	80	57.3	38	85	49.4	38	74	54.2	33	85
1953	54.7	33	79	59.2	36	81	58.2	37	85	67.8	40	83	59.0	33	85
1954	--	--	--	64.7	37	84	61.4	36	82	63.4	37	85	63.0	36	85
1955-58, no data															
1959	--	--	--	--	--	--	68.3	42	88	67.3	42	89	67.7	42	89
1960	62.0	32	84	55.1	35	85	65.1	36	87	58.5	41	77	61.2	32	87
1961	54.6	37	84	67.7	34	83	71.3	41	87	62.7	41	84	69.3	34	87
1962	64.6	46	81	59.3	38	86	59.1	38	84	54.2	41	81	59.2	38	86
1963	--	--	--	53.0	37	83	63.6	40	84	--	--	--	57.8	37	84
1964	54.0	33	83	54.6	36	81	64.0	36	88	60.1	33	81	59.7	33	88
1965	56.0	30	82	62.5	37	85	65.7	30	87	63.9	40	87	62.5	30	87
1966	59.4	31	85	66.1	34	85	65.2	30	86	63.2	38	85	64.0	30	86
1967	53.3	30	85	66.4	32	88	63.4	35	88	56.8	38	84	60.7	30	88
1968	53.6	32	85	58.2	35	89	62.8	39	88	60.6	30	83	59.4	30	89
1969	55.5	35	85	54.6	35	82	62.4	31	88	51.7	33	78	57.2	31	88
1970	48.4	30	83	48.6	36	81	61.3	40	86	64.1	37	82	56.4	30	86
1971	57.7	38	82	56.8	39	83	64.1	44	82	61.9	49	79	59.3	38	83
1972	63.0	36	79	71.8	39	81	73.4	46	87	61.0	35	80	68.5	35	87
1973	51.1	32	83	70.0	39	83	--	--	--	--	--	--	62.8	32	83
1974	58.4	33	84	56.7	34	89	60.0	36	88	63.2	36	84	59.9	33	89
1975	61.3	33	89	46.0	31	67	63.4	36	87	55.0	39	85	56.1	31	89
1976	58.0	36	81	55.2	36	79	56.8	38	78	63.1	40	81	59.5	36	81
1977	63.1	37	88	57.0	30	88	--	--	--	--	--	--	60.6	30	88
Mean	57.30	35.7	82.8	58.42	34.9	83.0	62.76	37.3	85.4	60.03	38.7	81.9	60.45	33.43	86.11
Min.	48.4	30	68	45.7	30	67	56.8	30	78	49.4	30	74	51.7	30	81
Max.	64.6	50	89	71.8	39	89	73.4	46	88	67.8	49	89	69.3	42	89

Figure 1. Annual fork length statistics for skipjack tuna from the Hawaiian pole-and-line fishery.

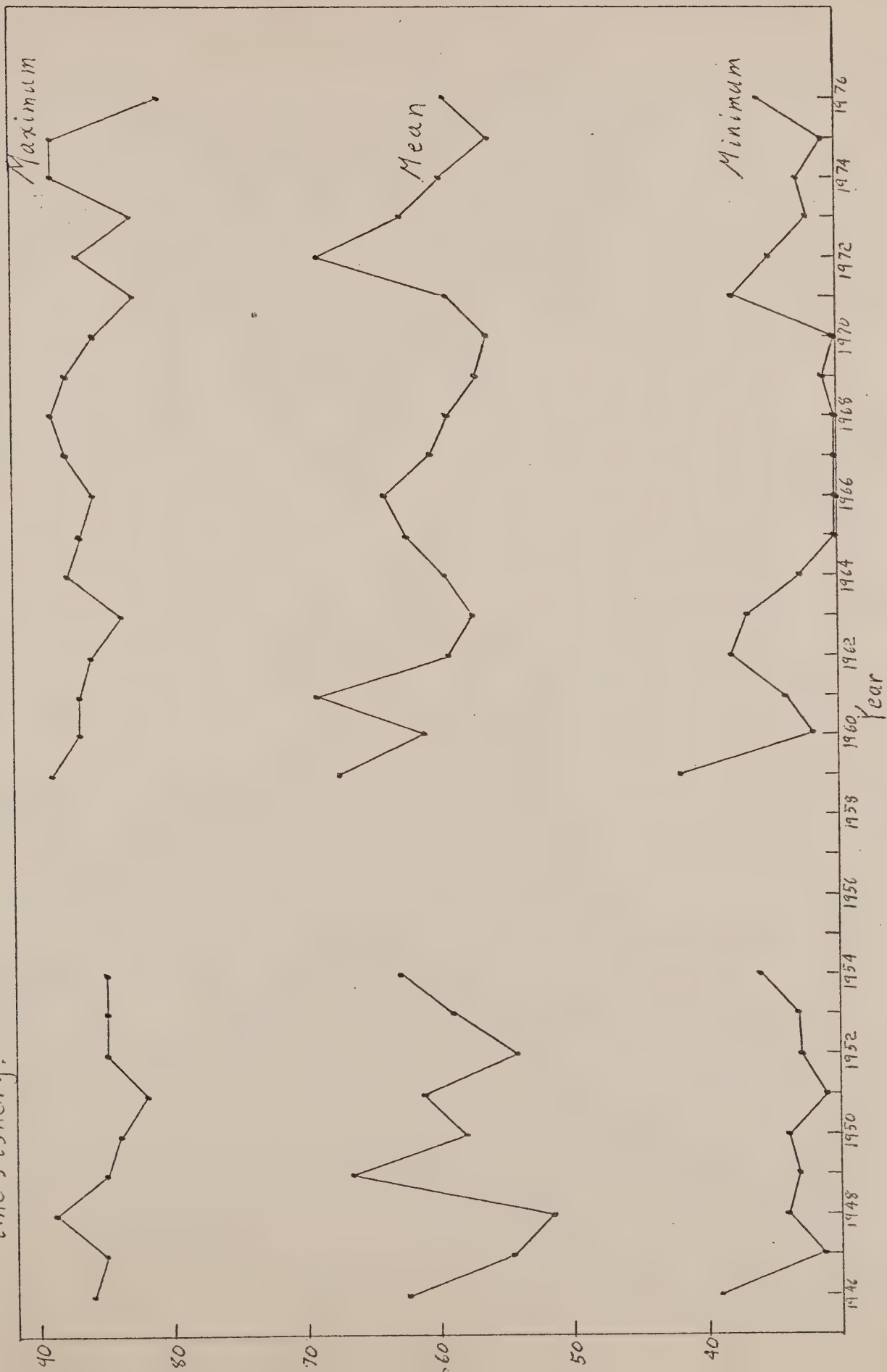


Figure 2. Mean quarterly fork length statistics for skipjack tuna from the Hawaiian pole-and-line fishery, 1946-54 and 1959-76.

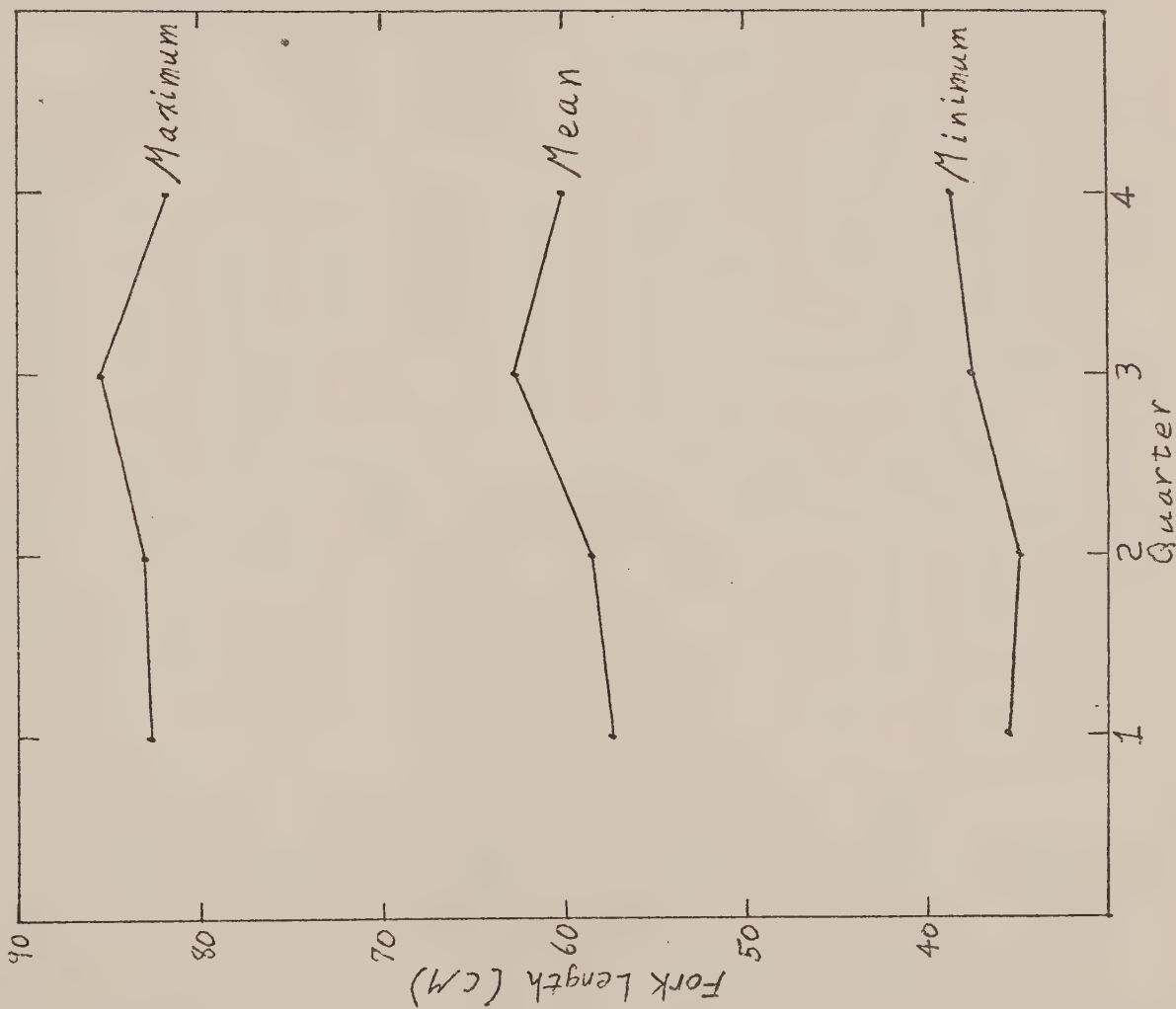


Figure 3. Mean monthly fork length statistics for the third quarter for skipjack tuna from the Hawaiian pole-and-line fishery, 1946-54 and 1959-76.

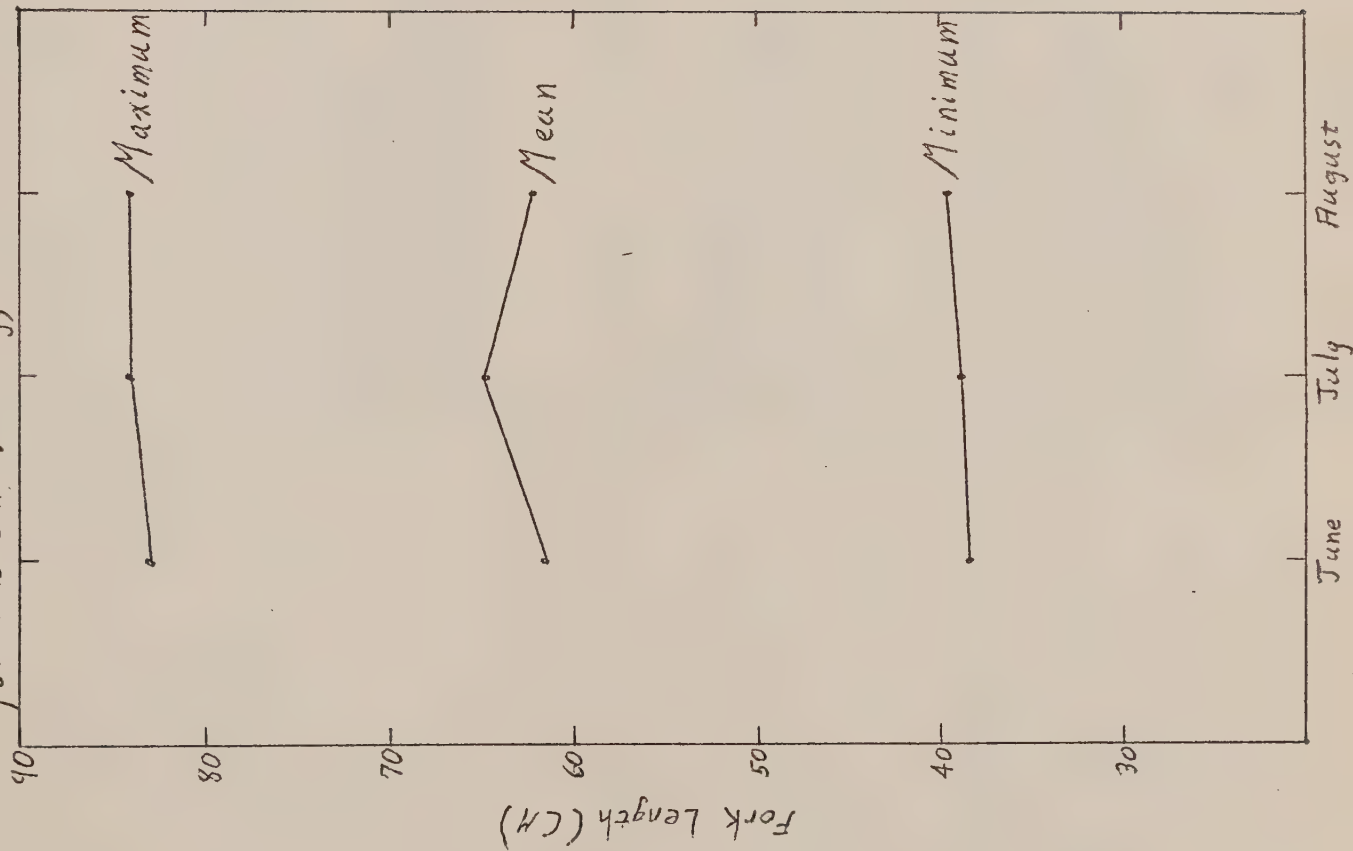
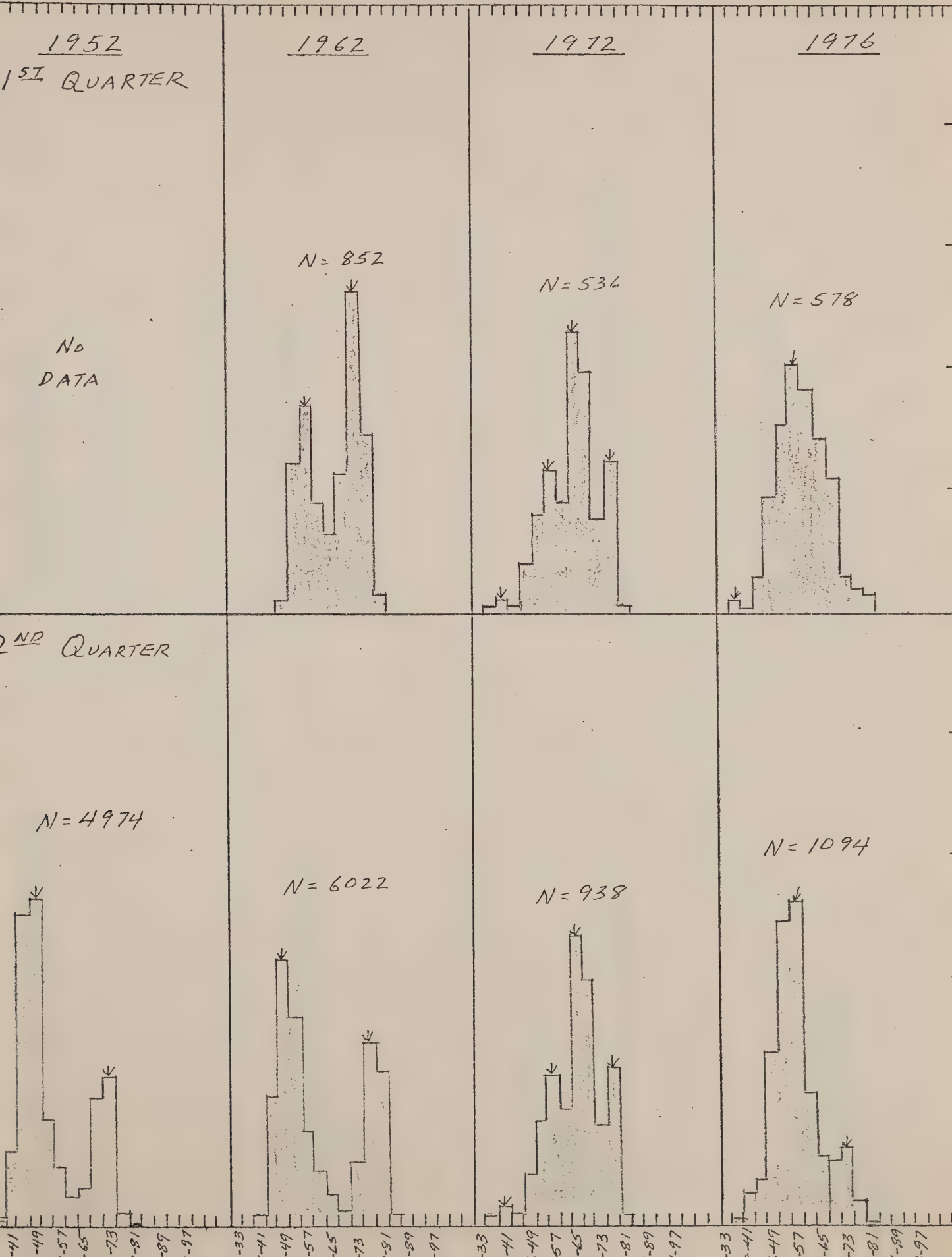


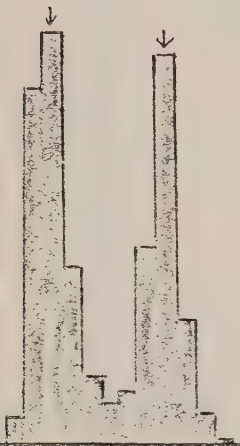
Figure 4. Quarterly fork length frequency distributions for skipjack tuna from the Hawaiian pole-and-line fishery; 1952, 1962, 1972 and 1976.



1952

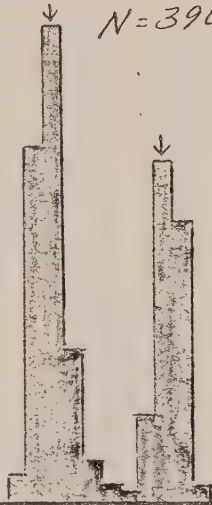
3RD QUARTER

N = 6197



1962

N = 3909



1972

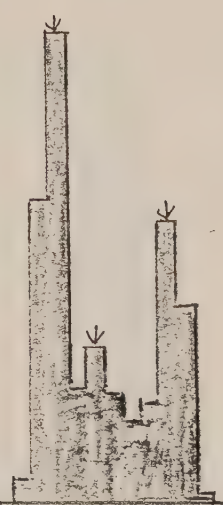
N = 806

54.2%

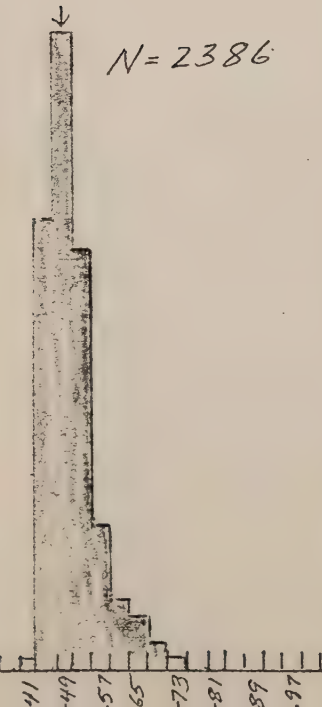


1976

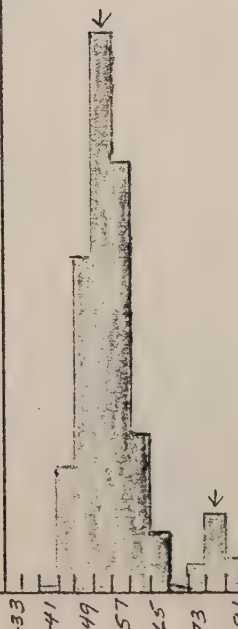
N = 751

4TH QUARTER

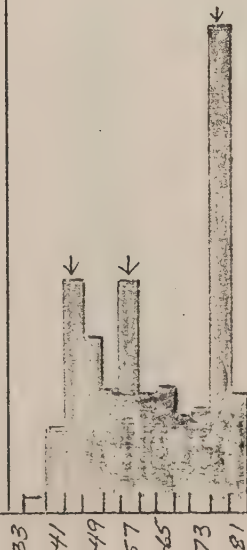
N = 2386



N = 886



N = 555



N = 2131

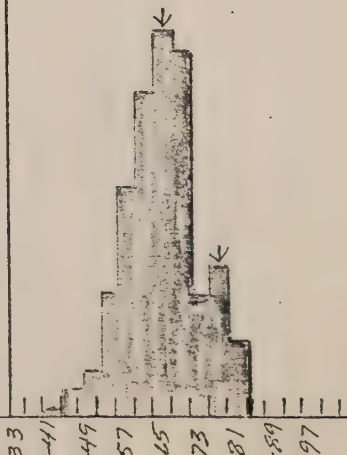
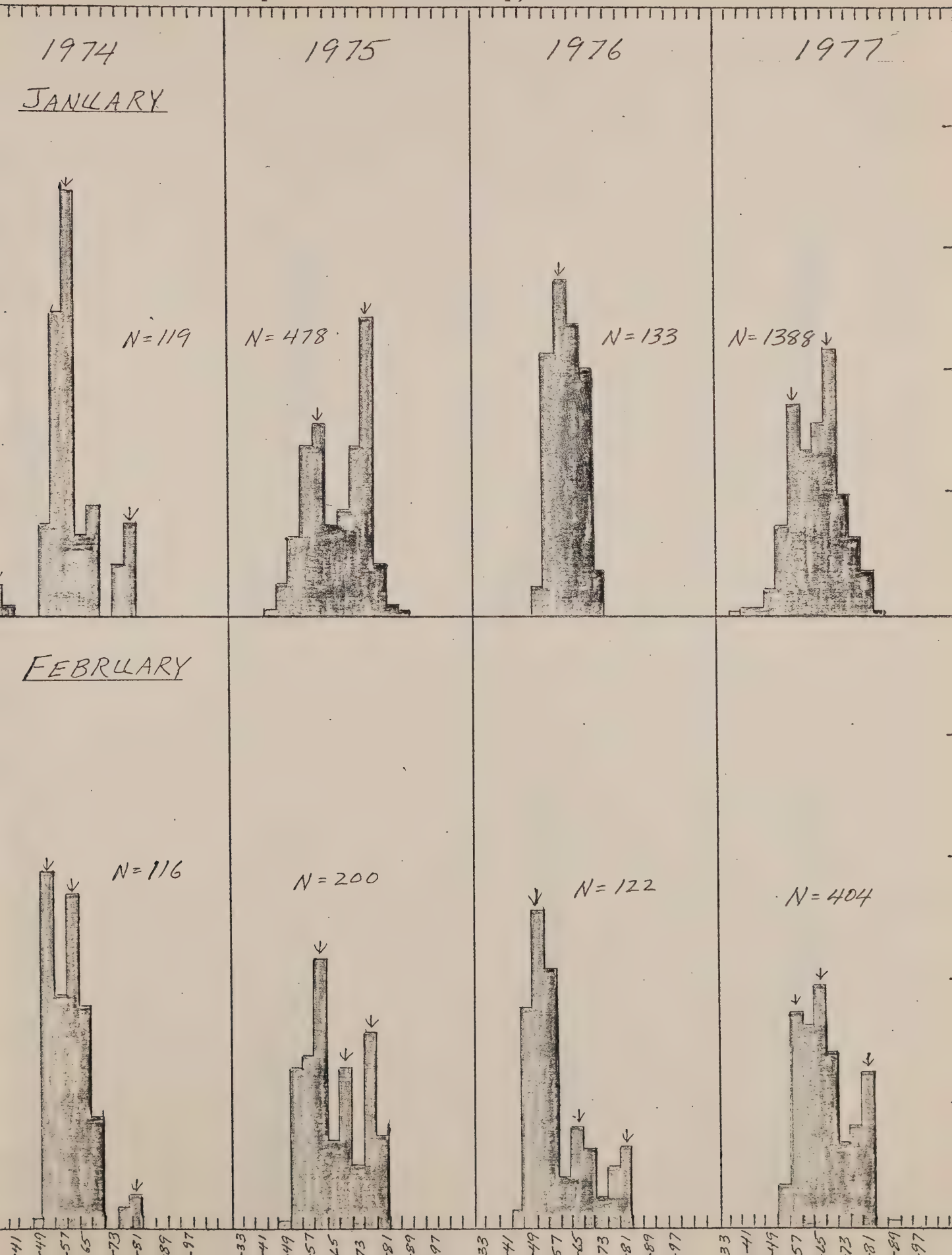


Figure 5. Monthly fork length frequency distributions for skipjack tuna from the Hawaiian pole-and-line fishery; 1974-75.



1974

1975

1976

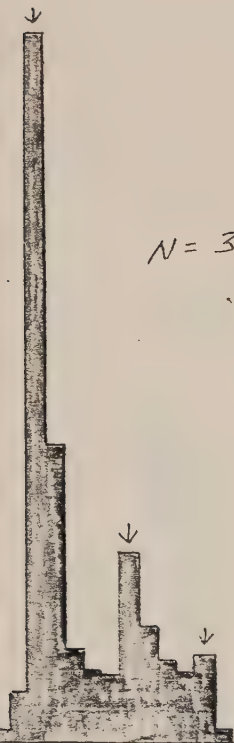
1977

MARCH $N=240$ $N=370$ $N=323$ $N=206$ APRIL $N=119$ $N=395$ $N=328$ $N=421$

1974

MAY

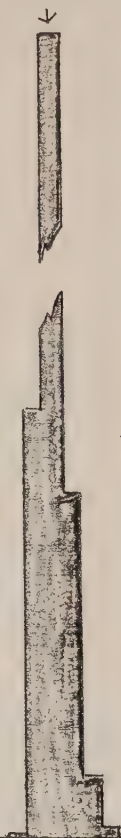
N = 322



1975

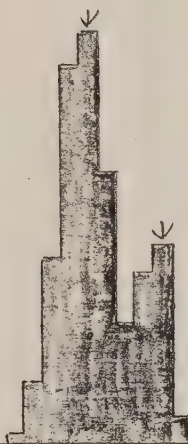
52.8%

N = 407



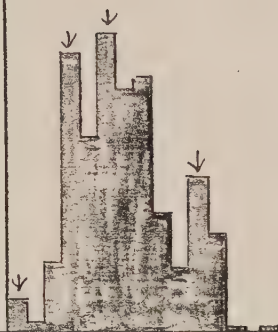
1976

N = 329

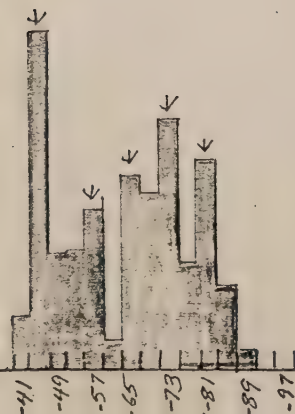


1977

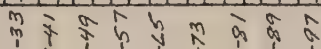
N = 700

JUNE

N = 438



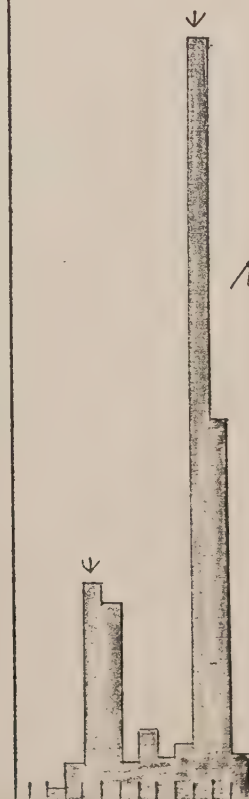
NO DATA



N = 437



N = 263

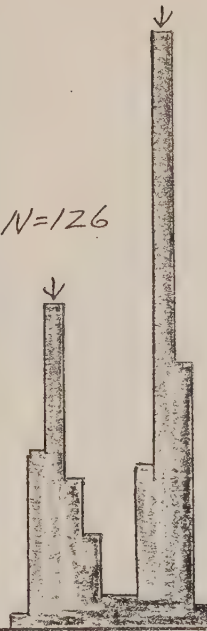
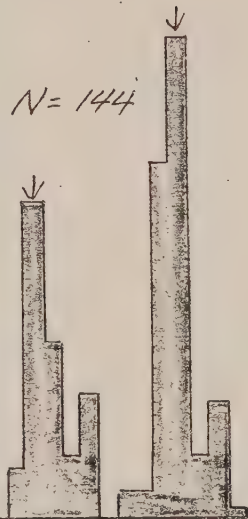
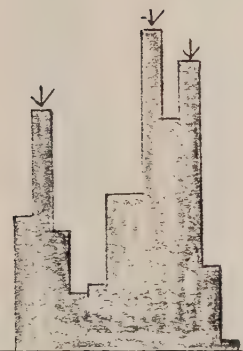
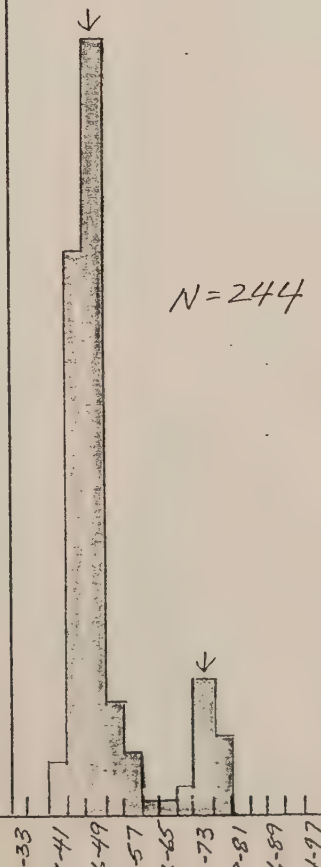
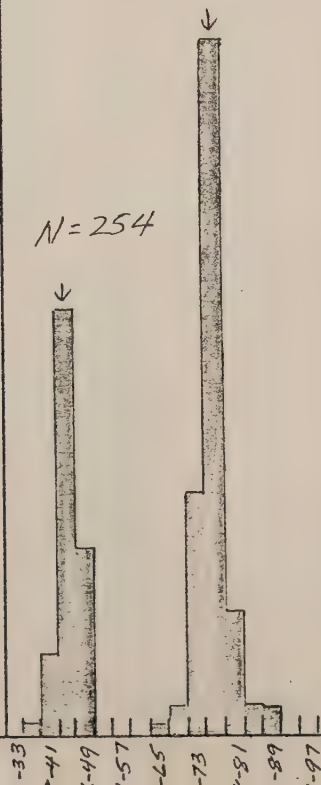
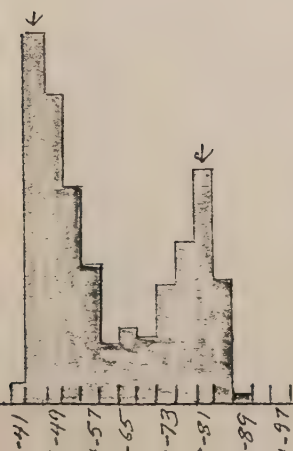


1974

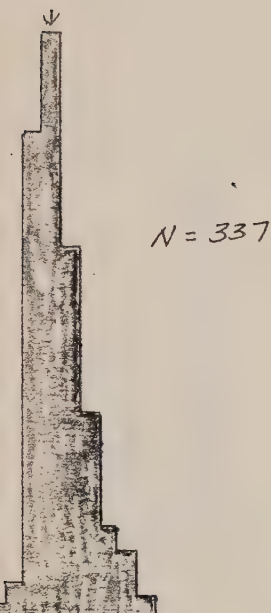
1975

1976

1977

JULY $N=736$ $N=144$ $N=126$ AUGUST $N=695$ $N=254$ $N=244$ 

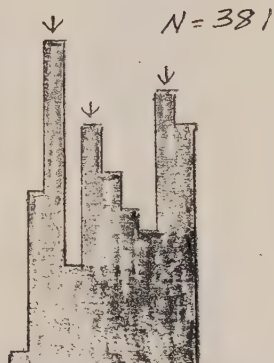
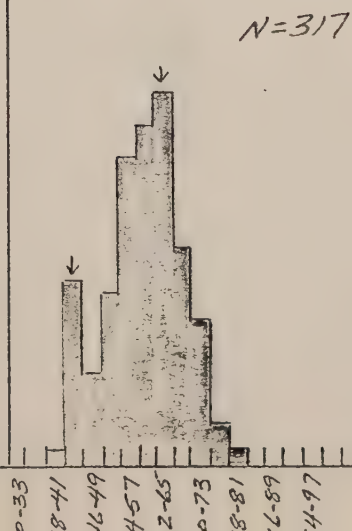
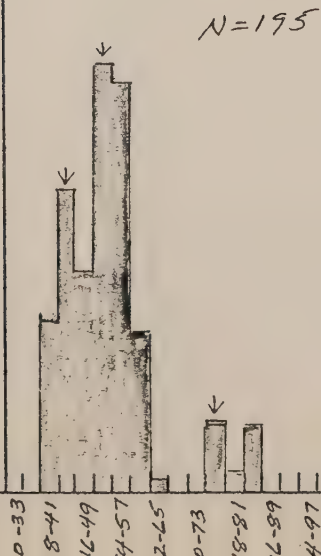
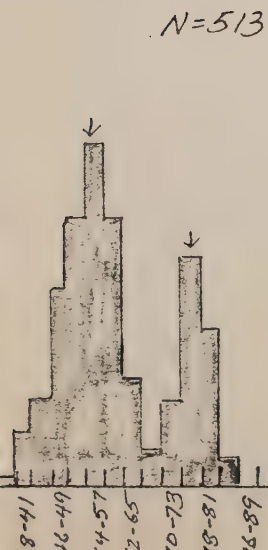
1974

SEPTEMBER

1975

NO DATA

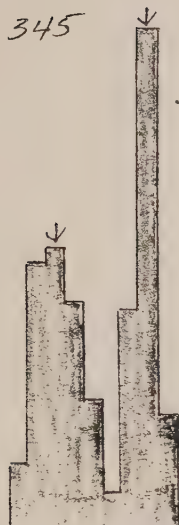
1976

OCTOBER

1974

NOVEMBER

N = 345



1975

66.7%

N = 15

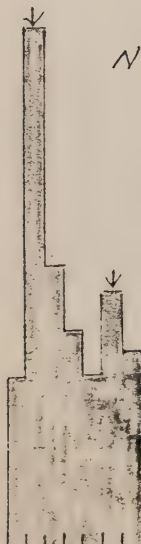


1976

N = 1060

DECEMBER

N = 85



54.0%

N = 50



N = 754



8-41 16-49 4-57 2-65 10-73 18-81 16-89 4-97 0-33 8-41 16-49 4-57 2-65 10-73 18-81 16-89 4-97 0-33 8-41 16-49 4-57 2-65 10-73 18-81 16-89 4-97 0-33 8-41 16-49 4-57 2-65 10-73 18-81 16-89 4-97

HISTORICAL TRENDS IN CATCH, FISHING EFFORT,
AND CATCH PER UNIT EFFORT IN THE HAWAIIAN FISHERY
FOR SKIPJACK TUNA, KATSUWONUS PELAMIS, 1948-76

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Prepared for

Indo-Pacific Fishery Commission
Eighteenth Session and Symposium
Manila, Philippines

8-17 March 1978

February 1978

INTRODUCTION

The skipjack tuna fishery continues to be the most important fishery in the State of Hawaii, and the skipjack tuna, Katsuwonus pelamis L., continues to be the most important commercial species landed. In 1976 which was an average year for skipjack tuna landings, skipjack tuna made up 64% of the total fishes landed by weight and 43% by value of landings.

Most of the skipjack tuna landed are captured by the Hawaiian pole-and-line fleet that fishes mostly within a day's run of the main Hawaiian Islands. The number of full time vessels in the fleet now numbers 14. Most are aku sampans, which are generally made of wood and range from 27 to 77 gross tons, and there is a single modern, refrigerated vessel of 136 gross tons. There are also other vessels that fish only during the peak of the season. The anchovy, Stolephorus purpureus Fowler, is used as the primary bait species and its lack of hardiness limits trip length generally to 1 day and not more than 3 days. The abundance or availability of the bait often limits fishing activities, especially when skipjack tuna is most abundant.

Catch Trends

From 1928 to 1936, the mean annual catch of skipjack tuna was 2,400 metric tons (MT), and from 1937 to 1940, the mean rose to 5,000 MT. While fishing ceased during World War II (Uchida 1966), normal fishing activities were resumed by 1948.

From 1948 through 1976, the annual landing of skipjack tuna has averaged 4,400 MT (Table 1), which is somewhat less than the 1937-40 average. There seems to be no indication of an increase or decrease in the annual landings or of any other long-term trend though there is considerable year-to-year fluctuation (Figure 1). The largest catch (7,329 MT) occurred in 1965, and the smallest (2,293 MT) in 1975.

While there is no discernible long-term trend in the catches, there is of course a marked seasonal pattern. Averaged over 1948-76, the mean trend reaches its lowest point in February, rises to a peak in July, and then falls steadily to a low in December (Figure 2). The best year in the history of the fishery, 1965, followed essentially the same pattern but with the season peaking in May and persisting through September. The poorest year, 1975, actually started out better than the average, but the summer season catches never materialized.

Fishing Effort and Catch Per Unit Effort

Several attempts have been made to estimate the abundance of skipjack tuna using data from the Hawaiian fishery. Yamashita (1958) and Shippen (1961) both used uncorrected measures of fishing effort in terms of productive or effective trips. Uchida (1967) standardized fishing effort in terms of effective days fished by Class 2 vessels, where vessel classes were based on carrying capacities of the baitwells. In his latest analysis of the fishery Uchida (1976) standardized fishing effort in terms of days fished (effective days plus days of zero-catch) by Class 2 vessels, where

vessel classes were based on gross tonnage. The data presented here follow the computational procedures presented by Uchida (1976).

The catch per days fished by Class 1 and 2 vessels and their relative efficiency factors for both inshore and offshore zones are presented in Table 2. The inshore zone extends from just outside the reef to 37 km from shore, and the offshore zone extends outward of 37 km. While the catch per day fished is higher in the offshore zone, the relative efficiency factors are not statistically different ($t = 0.337$ with d.f. = 28), nor is there a correlation between the annual fluctuations for inshore and offshore zones ($r^2 = 0.0048$, $n = 29$). The annual geometric mean efficiency factor fluctuates considerably, but no discernible trend is apparent (Figure 3).

The apparent abundance of skipjack tuna was estimated using the formula

$$C/SDF = \frac{TC_1 + TC_2}{(EF)(DF_1) + DF_2}$$

where

TC_1 = total catch of Class 1 vessels,

TC_2 = total catch of Class 2 vessels,

EF = efficiency factor,

DF_1 = days fished among Class 1 vessels,

and

DF_2 = days fished among Class 2 vessels.

The relative fishing intensity for all skipjack tuna catches was estimated using

$$\text{Relative fishing intensity} = \frac{TC_s}{C/SDF}$$

where

TC_s = total state catch.

Estimates from these formulas are given in Table 1.

As can be seen from Figure 1, C/SDF follows the same annual trend as does the total catch but with less variation. Figure 4 shows the data from the viewpoint of the catch generated by the fishery being dependent on the relative abundance of the stock. The regression line shown in the figure has a correlation coefficient of 0.919 with $n = 29$.

As is typical of most skipjack tuna fisheries, no effect of the fishery on the stock can be demonstrated. Figure 5 shows the relationship between C/SDF and the relative fishing intensity and lags of 1 or 2 years or averaging of the relative fishing intensity over a 2-year period did not result in any significant improvement in the relationship.

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YAMASHITA, D. T.

1958. Analysis of catch statistics of the Hawaiian skipjack fishery. U.S. Fish Wildl. Serv., Fish. Bull. 58:253-278.

Table 1.--Total Hawaii landings of skipjack tuna from all fisheries and estimated statistics for catch per standard day fished, relative fishing intensity, catch per standard effective trip, and relative effective fishing intensity, 1948-76.¹

Year	Total catch (MT)	Catch per standard day fished (MT/SDF)	Relative fishing intensity (Class 2 days fished)	Catch per standard effective trip (MT/trip)	Relative effective fishing intensity (Class 2 trips)
1948	3,802.96	2.01	1,891	2.30	1,653
1949	4,488.23	2.53	1,773	2.85	1,575
1950	4,314.38	1.99	2,161	2.31	1,868
1951	5,863.37	2.93	2,001	3.28	1,788
1952	3,307.58	1.83	1,806	2.15	1,538
1953	5,470.15	2.14	2,552	2.46	2,224
1954	6,360.13	2.81	2,256	3.16	2,013
1955	4,397.43	1.95	2,248	2.26	1,946
1956	5,049.58	2.59	1,946	2.91	1,735
1957	2,780.66	1.61	1,726	1.90	1,464
1958	3,100.15	1.87	1,652	2.18	1,422
1959	5,630.65	2.93	1,919	3.26	1,727
1960	3,338.46	1.99	1,673	2.30	1,452
1961	4,941.66	2.69	1,835	3.01	1,642
1962	4,270.81	2.56	1,665	2.88	1,483
1963	3,673.86	2.15	1,712	2.48	1,481
1964	4,093.10	1.98	2,065	2.29	1,787
1965	7,328.96	3.29	2,221	3.54	2,070
1966	4,256.82	2.24	1,896	2.52	1,689
1967	3,646.80	1.99	1,832	2.30	1,586
1968	4,227.41	2.04	2,067	2.32	1,822
1969	2,704.94	1.63	1,658	2.02	1,339
1970	3,334.46	1.89	1,760	2.19	1,523
1971	6,051.39	3.07	1,971	3.33	1,815
1972	4,952.12	2.67	1,852	2.94	1,685
1973	4,876.71	2.59	1,880	2.94	1,661
1974	3,373.04	1.74	1,942	1.98	1,702
1975	2,292.57	1.16	1,969	1.48	1,551
1976	4,443.55	2.37	1,877	2.67	1,667

¹Data from 1948 to 1970 from Uchida (1976).

Table 2.--Catch per day fished and vessel efficiency factors by inshore and offshore areas by vessel classes 1 and 2, and the geometric mean vessel efficiency factor for each year, 1948-76.¹

Year	Inshore			Offshore			Geometric mean
	Class 1	Class 2	Efficiency factors	Class 1	Class 2	Efficiency factors	
1948	1.33	1.78	0.747	2.07	3.46	0.598	0.668
1949	1.56	2.24	0.696	2.54	4.12	0.616	0.655
1950	1.34	1.74	0.770	2.10	3.38	0.621	0.692
1951	1.64	2.59	0.633	2.60	3.58	0.726	0.678
1952	1.31	1.66	0.789	1.31	2.19	0.598	0.687
1953	1.53	1.98	0.773	2.37	2.69	0.881	0.825
1954	1.36	2.54	0.535	2.89	3.80	0.760	0.638
1955	1.39	1.99	0.698	2.08	2.32	0.896	0.791
1956	1.90	2.36	0.805	2.30	3.27	0.703	0.752
1957	1.18	1.63	0.724	1.28	1.61	0.795	0.759
1958	1.17	1.87	0.626	1.79	2.36	0.758	0.689
1959	1.97	3.03	0.650	2.37	2.91	0.814	0.728
1960	1.32	2.02	0.653	1.94	2.40	0.803	0.727
1961	1.82	2.37	0.768	2.42	4.05	0.598	0.677
1962	1.49	2.45	0.608	2.22	3.43	0.647	0.627
1963	1.17	1.77	0.661	1.87	3.55	0.527	0.590
1964	1.40	1.69	0.828	2.07	2.90	0.714	0.769
1965	2.39	2.90	0.824	3.32	4.01	0.828	0.826
1966	1.54	1.82	0.846	1.93	2.91	0.663	0.749
1967	1.47	1.84	0.799	1.65	2.31	0.714	0.755
1968	1.57	1.68	0.934	2.04	2.93	0.696	0.807
1969	1.12	1.43	0.783	1.53	2.26	0.699	0.740
1970	1.32	1.74	0.759	1.30	2.36	0.551	0.646
1971	2.38	2.98	0.800	3.03	3.49	0.867	0.833
1972	1.49	2.28	0.651	2.55	3.74	0.681	0.666
1973	1.16	2.30	0.506	2.42	3.37	0.719	0.603
1974	1.15	1.64	0.699	1.57	2.10	0.749	0.724
1975	0.88	1.10	0.804	1.08	1.45	0.741	0.772
1976	1.44	2.37	0.607	2.00	2.65	0.755	0.677

¹Data from 1948 to 1970 from Uchida (1976).

Figure 1. Historical trend in total catch and catch per standard day fished for skipjack tuna in Hawaii, 1948-76.

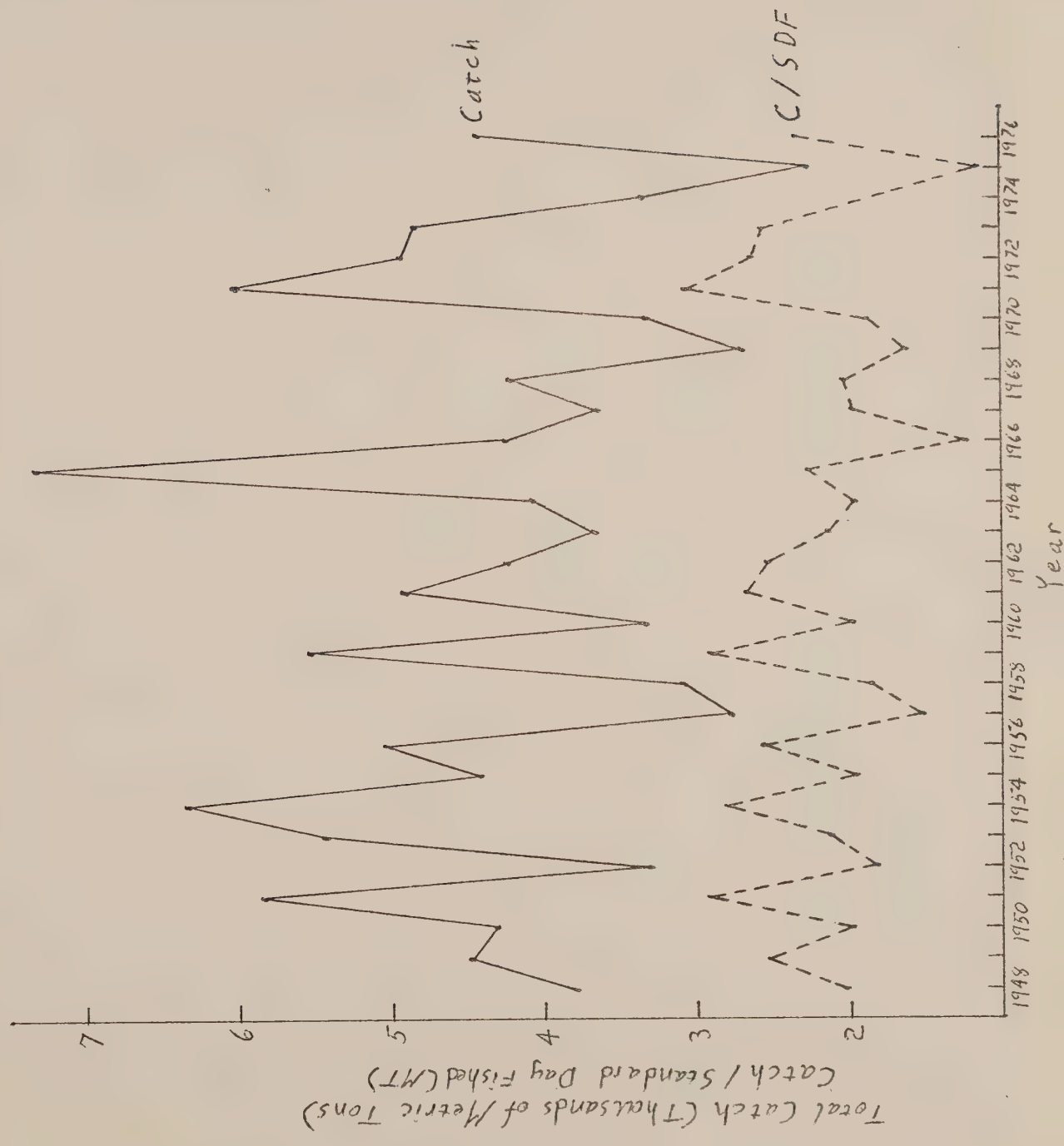


Figure 2. Seasonal trends of skipjack tuna catches in Hawaii for the long-term mean over 1948-76, the best year 1965, and the poorest year 1975.

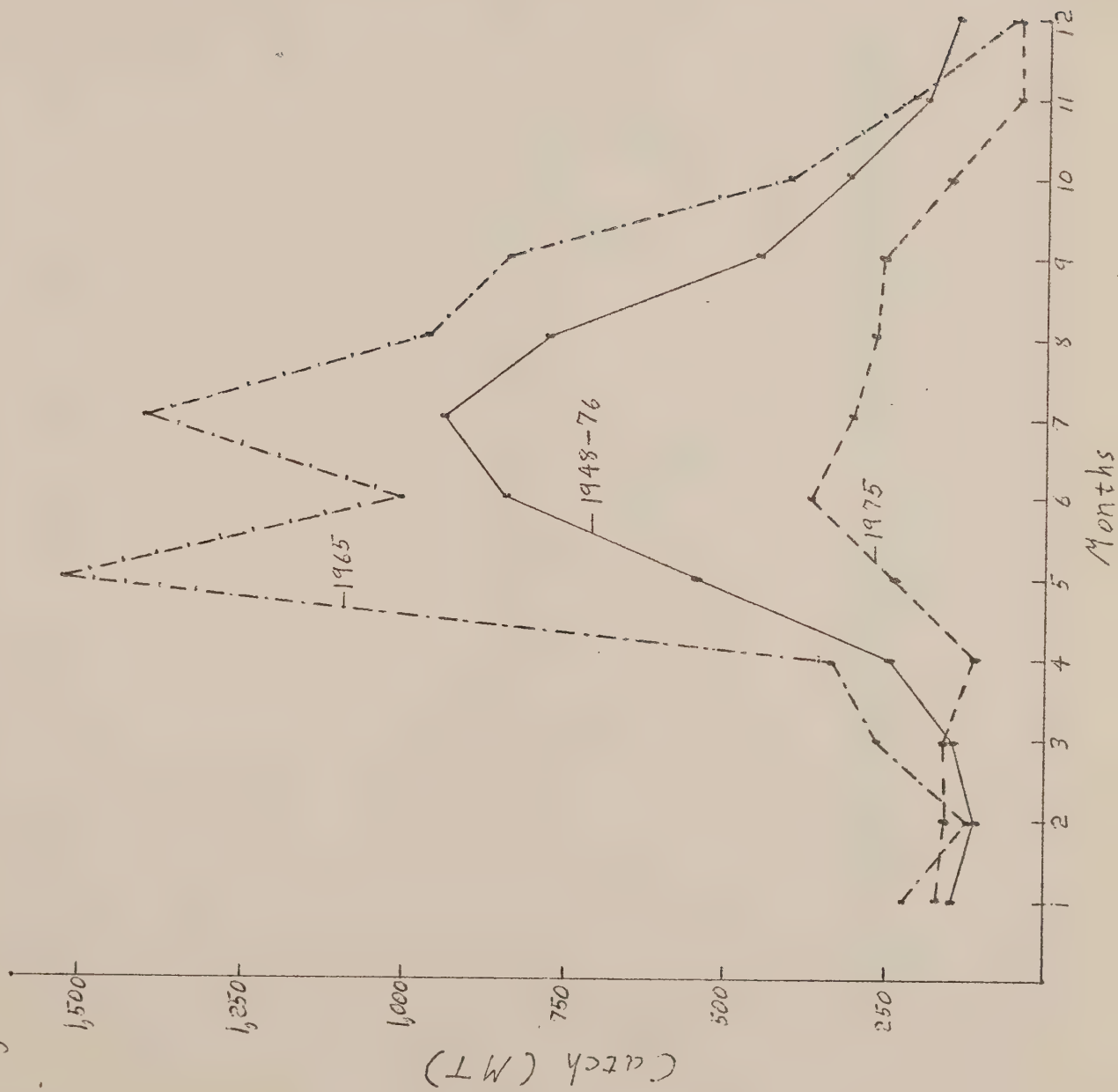


Figure 3. Annual geometric mean of the vessel efficiency factors, 1948-76.

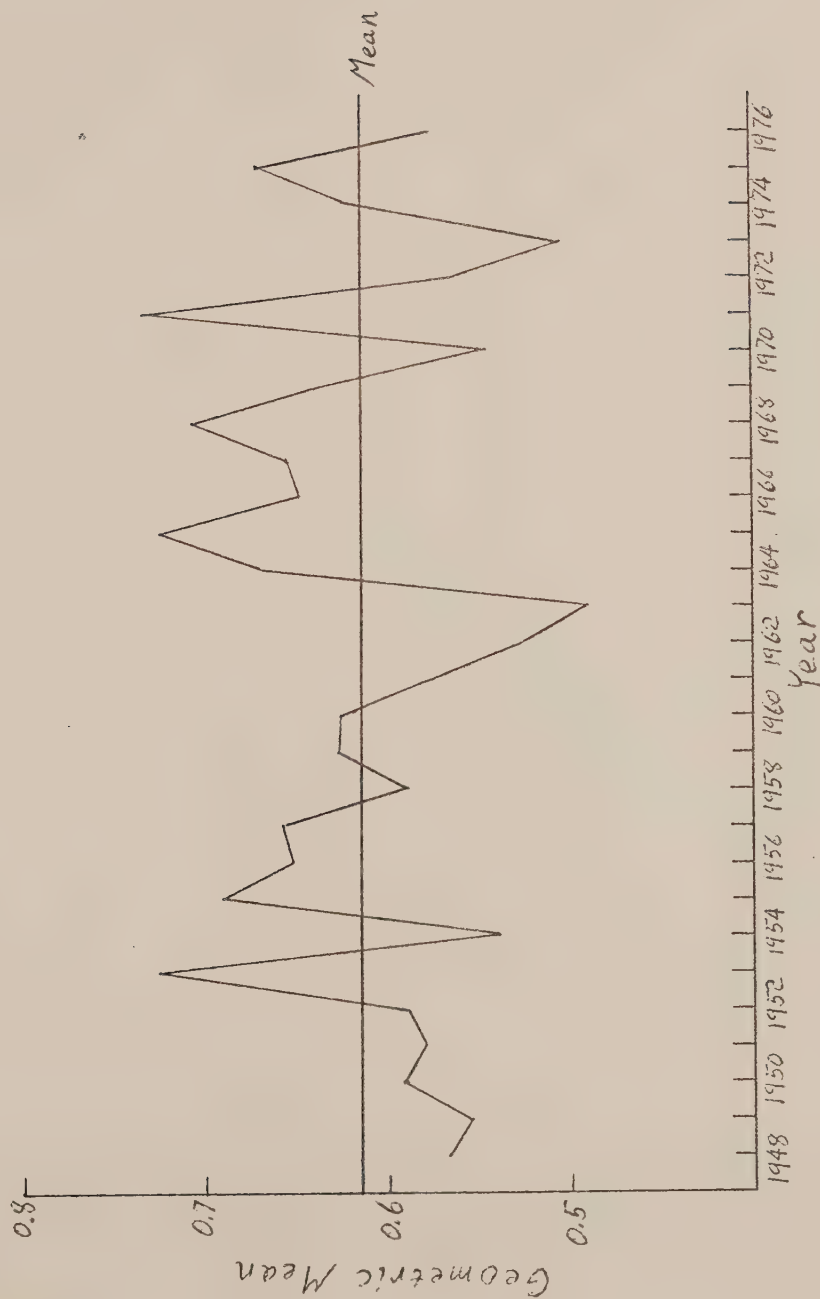


Figure 4. Relationship between catch and catch per standard day fished for skipjack tuna in Hawaii, 1948-76.

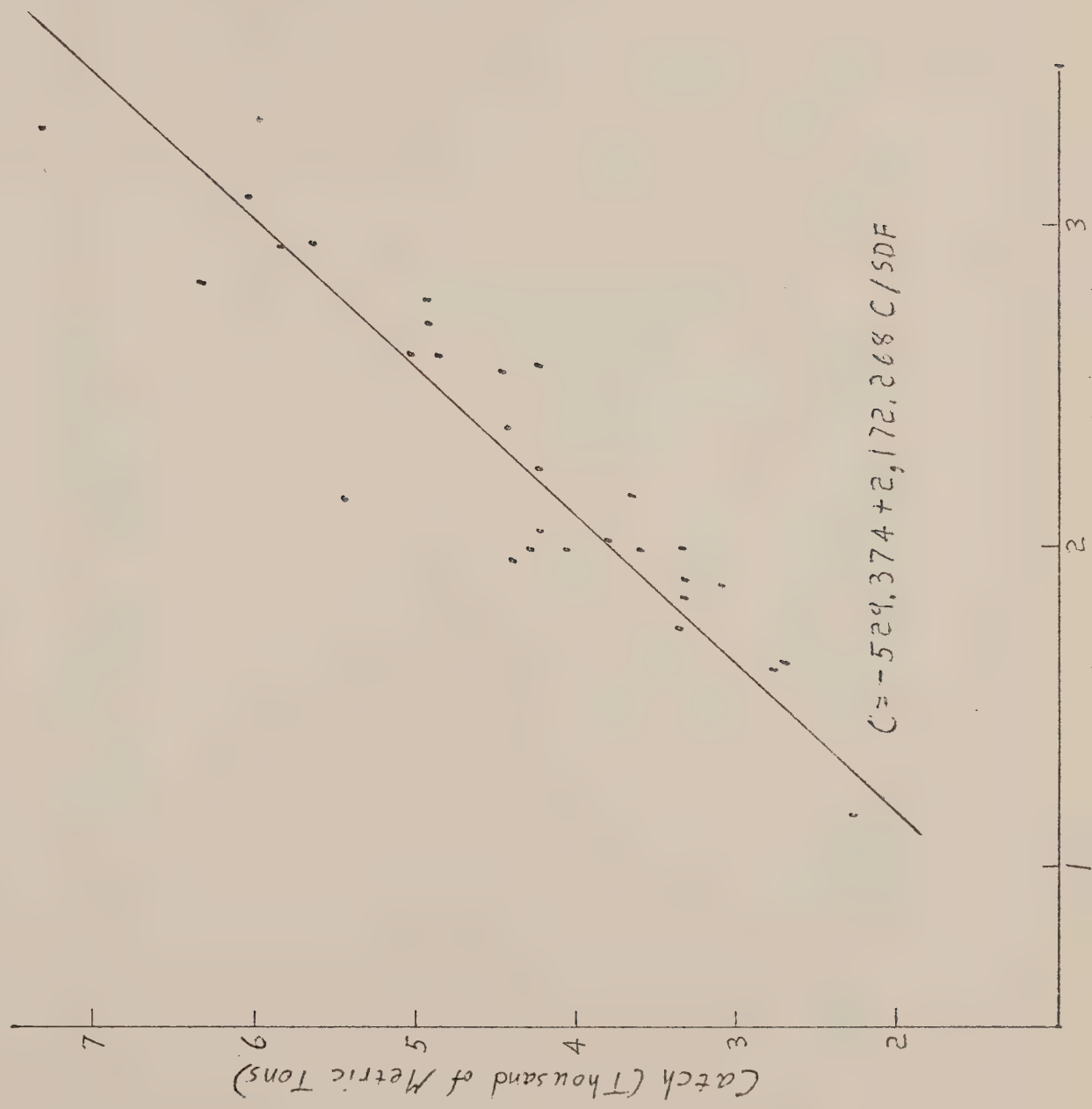
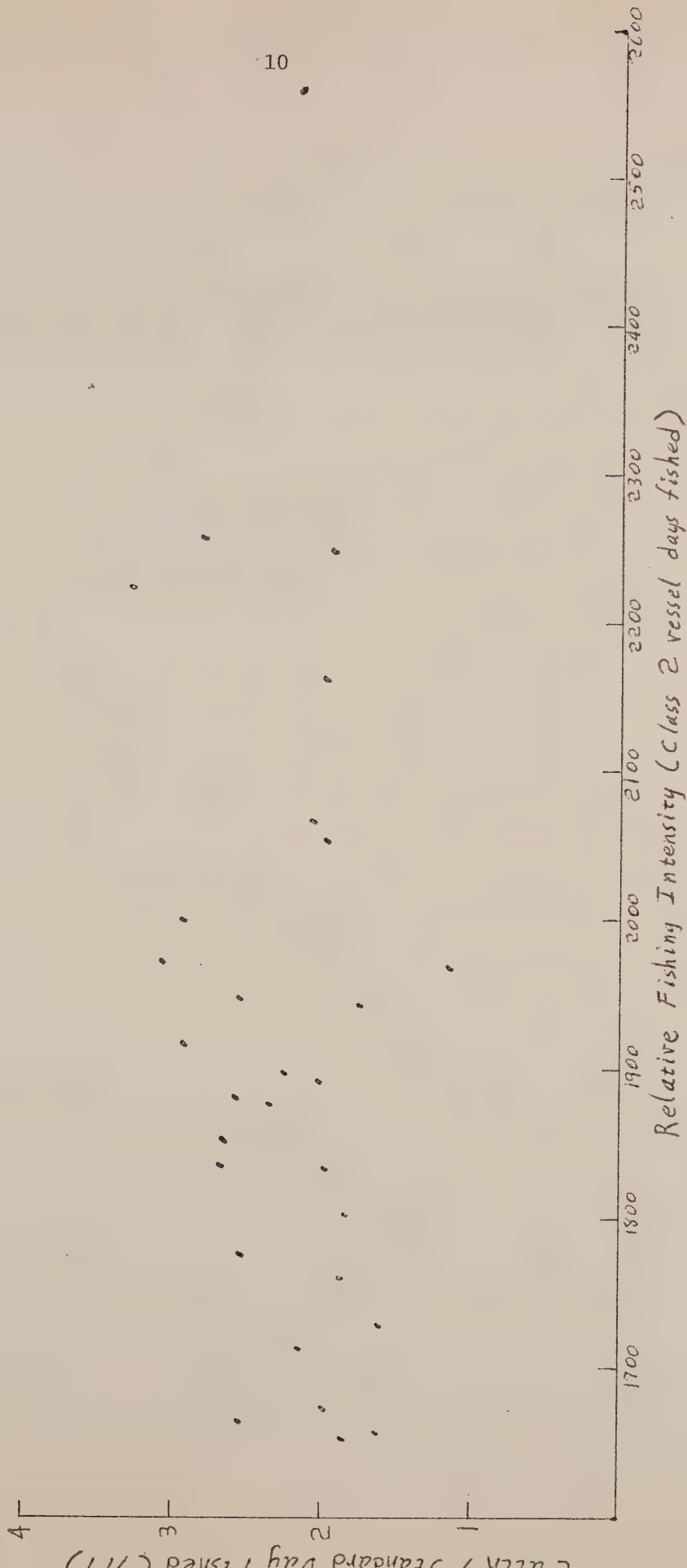


Figure 5. Relationship between measure of abundance and fishing intensity within same year for skipjack tuna, 1948-76.



RECENT TRENDS IN CATCH, FISHING EFFORT, AND CATCH PER UNIT EFFORT
FOR THE SOUTH PACIFIC ALBACORE FISHERY BASED IN AMERICAN SAMOA, 1954-76.

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INTRODUCTION

While there was some exploratory longline fishing by the Japanese in 1952 and 1953, the South Pacific tuna longline fishery became firmly established in January 1954 when a cannery in Pago Pago, American Samoa contracted with seven Japanese tuna longline vessels to supply it with tuna. A second cannery was opened in 1963. In 1954 and 1955, the landings of yellowfin tuna, Thunnus albacares (Bonnaterre), exceeded that for albacore, T. alalunga (Bonnaterre), but the fishery soon developed into an albacore fishery with other tuna species being of minor importance. Other bases have been established at Espiritu Santo, New Hebrides (1958); Levuka, Fiji Islands (1963); and Tahiti (1971). Home-based tuna vessels from Japan and to a lesser extent from Korea and the Republic of China (Taiwan), also participate in the fishery.

Catch Trends

As mentioned earlier, the catch of yellowfin tuna exceeded that of albacore in 1954 and 1955. From 1955 through about 1964, the catch of albacore increased fivefold while that for yellowfin tuna remained stable (Table 1, Figure 1). The catch of albacore continued to increase through 1973 when a catch of 30,148 metric tons (MT) was made. Following 1973, the catch declined drastically in response to declining catch rate and a decreasing fleet size. The catch of bigeye tuna, T. obesus (Lowe), has generally been much less than for either albacore or yellowfin tuna, but in the last few years the bigeye tuna catch has remained relatively stable while that for the other tuna species has declined. Billfish catch has never been significant, and it too has declined in recent years.

When the catch is presented according to the national origin of the longline vessels (Table 2), it can be seen that each of the fleets has concentrated its fishing effort on albacore. The only exceptions are in 1954-55 by Japanese vessels and in 1975 by Korean vessels.

Fishing Units

Longline vessels from Japan began fishing from Pago Pago, American Samoa in January 1954, had the fishery to themselves until 1959, and withdrew from the fishery after 1972 (Figure 2). Vessels from Korea joined the fishery in 1959, and vessels from Taiwan did so in 1964. The number of vessels reached a high of 309 (156 Korean and 153 Taiwanese) in 1973, and then declined drastically to 133 by 1976.

The mean size of the longline tuna vessels remained at approximately 100 gross tons through the first decade of the fishery (Figure 3). Larger vessels began entering the fishery toward the end of the first decade, and smaller vessels too, but the resultant mean size increased to 175 gross tons by 1975. The largest vessel to participate in the fishery has been a 680-gross ton Korean vessel, while the smallest has been a 23-gross ton Taiwanese vessel.

The number of fishing trips (Figure 4) made by the longline vessels based in American Samoa has followed a trend similar to that for the number

of vessels. The increase in the number of trips through 1963 was due to Japanese vessels while the continued increase and subsequent decrease were due to Korean and Taiwanese vessels. The greatest number of trips was 872 in 1973. By 1976, there were only 265 trips, which is comparable to the number made in 1956 and 1961.

Fishing Effort

Two measures of fishing effort collected are the number of days fished and the number of hooks fished. Since the number of hooks fished is collected from a variable portion of the fleet, it gives a biased picture of the total fishing effort expended by the fleet and will not be presented here. However, the number of hooks fished will be used in calculating an index of relative abundance.

The number of days fished increased slowly through the first decade of the fishery, but then rose rapidly to a high of 47,549 days fished in 1973 (Figure 5). That is a fivefold increase in 9 years. Subsequently, the amount of fishing effort has declined sharply and reached 16,111 days in 1976, which is comparable to the amount of fishing effort expended over a decade ago.

Indexes of Relative Abundance

Estimates of relative abundance have been calculated in terms of metric tons per day fished and number caught per 100 hooks fished for albacore, yellowfin tuna, and bigeye tuna (Table 3). Also metric tons per trip has been included for comparison with valid measures of relative abundance. The diagram of metric tons per day fished shows a continuous decline in the relative abundance of the albacore stock from 1957 through 1975 (Figure 6). The decline is an impressive 76.0% reduction in the relative abundance of the albacore stock in 20 years of fishing. The number caught per 100 hooks fished shows essentially the same decline in relative abundance. The increase in relative abundance in 1976 may be in response to the reduced amount of fishing effort for the last few years or it may represent an increase in recruitment. In monthly plots of the number caught per 100 hooks fished (not presented here), the index of relative abundance during the peak of the southern winter, which is when the youngest albacore are caught in the southern extremes of the fishery, shows a steady decline from 1970 to 1974. In 1975, the southern winter fishery on small albacore failed to materialize. In 1976, the fishery materialized but the number caught per 100 hooks fished was the smallest on record except for 1975.

A generalized production model assessment of the status of the South Pacific albacore fishery by Skillman (1975) indicated that optimum catch per unit effort in order to maintain maximum sustainable yield was about 0.79 metric ton per day fished. This level of relative abundance was passed by the fishery in about 1970. The precipitous decline in relative abundance indicates that the albacore stock has been overfished and should be allowed to rebuild. The decline in the index of relative abundance during the southern winter fishery for small albacore may indicate that

the adult stock has been reduced to such an extent that recruitment has been impaired.

The indexes of relative abundance for yellowfin tuna and bigeye tuna do not indicate any long-term trends.

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Table 1.--Total catch (metric tons) by species and by year of capture, 1954-76, for the American Samoa fishery.

Year	Albacore	Yellowfin tuna	Bigeye tuna	Billfishes
1954	349	607	27	--
1955	2,110	2,260	24	--
1956	3,706	2,107	216	--
1957	6,029	1,599	315	--
1958	9,935	2,486	473	69
1959	10,292	1,776	447	110
1960	11,191	1,132	246	75
1961	9,740	1,328	158	75
1962	13,326	1,403	557	77
1963	14,650	2,145	1,609	168
1964	10,791	2,464	1,595	160
1965	15,459	4,476	2,933	417
1966	25,570	6,545	4,537	559
1967	28,310	5,326	5,540	405
1968	17,723	7,337	2,769	649
1969	18,731	8,139	3,221	1,153
1970	23,876	7,697	2,975	1,017
1971	22,193	8,567	2,058	1,988
1972	20,168	12,777	3,140	4,651
1973	30,148	10,480	4,496	3,925
1974	14,641	7,278	3,405	2,671
1975	7,840	6,142	4,349	1,204
1976	9,855	5,026	2,710	602

Table 2.--Catch (metric tons) of albacore and yellowfin tuna by nationality of vessel and by year of capture for the fishery based in American Samoa, 1954-76.

Year	Albacore			Yellowfin tuna		
	Japan	Korea	Taiwan	Japan	Korea	Taiwan
1954	349	--	--	603	--	--
1955	2,110	--	--	2,260	--	--
1956	3,706	--	--	2,107	--	--
1957	6,004	--	--	1,577	--	--
1958	9,784	146	--	2,412	70	--
1959	9,834	456	--	1,706	67	--
1960	10,581	610	--	1,047	84	--
1961	9,225	330	--	1,231	46	--
1962	12,605	635	--	1,349	47	--
1963	12,682	1,461	--	1,879	261	--
1964	8,097	1,850	556	1,943	411	111
1965	9,518	4,350	1,590	2,404	1,426	646
1966	9,086	9,123	7,361	2,429	2,012	2,104
1967	7,528	9,636	11,147	1,144	2,013	2,169
1968	3,156	6,349	8,218	1,052	2,979	3,305
1969	1,560	10,184	6,987	641	4,914	2,584
1970	952	11,942	10,982	226	3,664	3,808
1971	380	11,780	10,140	75	3,731	4,761
1972	60	9,863	10,244	55	6,648	6,074
1973	--	16,767	13,381	--	6,748	3,732
1974	--	6,844	7,798	--	5,195	2,083
1975	--	3,443	4,397	--	4,593	1,549
1976	--	5,475	4,380	--	4,059	967

Table 3.--Indexes of relative abundance for albacore, yellowfin tuna, and bigeye tuna
for the longline fishery based in American Samoa, 1954-76.

Year	Albacore			Yellowfin tuna			Bigeye tuna		
	MT/trip	MT/day fished	Number/100 hooks ¹	MT/trip	MT/day fished	Number/100 hooks ¹	MT/trip	MT/day fished	Number/100 hooks ¹
1954	5.5	--	--	9.5	--	--	0.4	--	--
1955	14.9	--	--	15.9	--	--	0.2	--	--
1956	14.1	--	--	8.0	--	--	0.8	--	--
1957	17.1	2.5	--	4.5	0.7	--	0.9	0.1	--
1958	22.3	1.8	--	5.6	0.5	--	1.1	0.1	--
1959	28.7	2.0	--	4.9	0.3	--	1.2	0.1	--
1960	39.3	1.7	--	4.0	0.2	--	0.9	0.0	--
1961	35.3	1.8	--	4.8	0.2	--	0.6	0.0	--
1962	36.0	1.6	8.44	3.8	0.2	0.32	1.5	0.1	0.23
1963	29.8	1.2	5.23	4.4	0.2	0.49	3.3	0.1	0.58
1964	28.5	1.2	4.96	6.5	0.3	0.71	4.2	0.2	0.51
1965	32.2	1.0	4.57	9.3	0.3	0.81	6.1	0.2	0.58
1966	35.1	1.1	5.20	9.0	0.3	0.65	6.2	0.2	0.50
1967	35.5	1.0	4.48	6.7	0.2	0.45	6.9	0.2	0.46
1968	30.5	0.7	3.43	12.6	0.3	1.01	4.8	0.1	0.47
1969	34.1	0.8	3.64	14.8	0.3	0.81	5.9	0.1	0.45
1970	37.2	0.9	3.98	12.0	0.3	0.68	4.6	0.1	0.30
1971	35.6	0.7	3.33	13.7	0.3	0.81	3.3	0.1	0.32
1972	31.8	0.6	2.87	20.1	0.4	0.92	4.9	0.1	0.34
1973	34.6	0.6	3.04	12.0	0.2	0.43	5.2	0.1	0.26
1974	21.9	0.4	1.82	10.9	0.2	0.50	5.1	0.1	0.24
1975	19.9	0.3	1.12	15.6	0.3	0.70	11.0	0.2	0.60
1976	37.2	0.6	1.89	19.0	0.3	0.47	10.2	0.2	0.37

¹Ratio of averages.

Figure 1. Total catch by species by year of capture for the fishery in American Samoa, 1954-76.

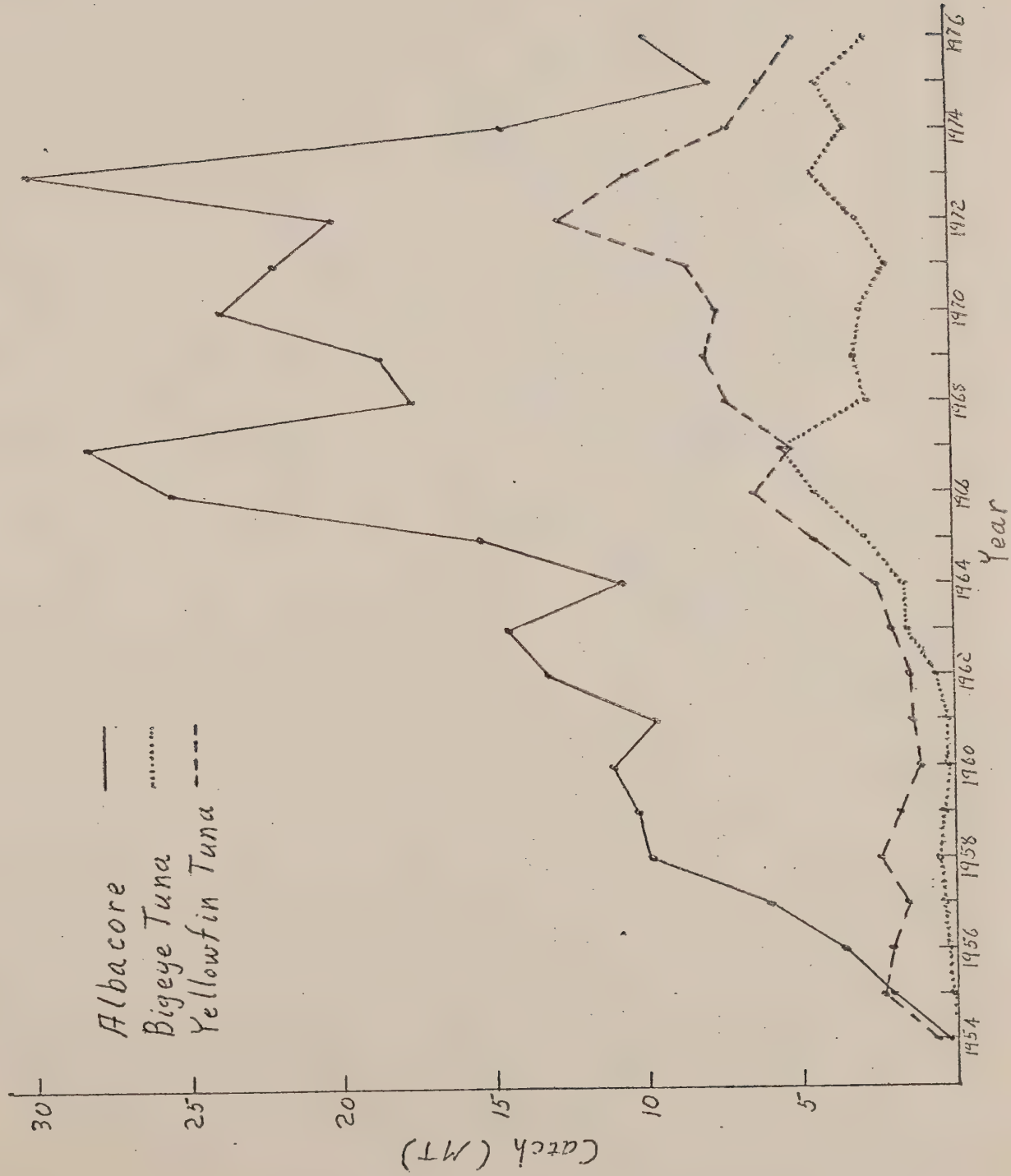


Figure 2. Number of longline vessels based in American Samoa, by nationality, 1954-76.

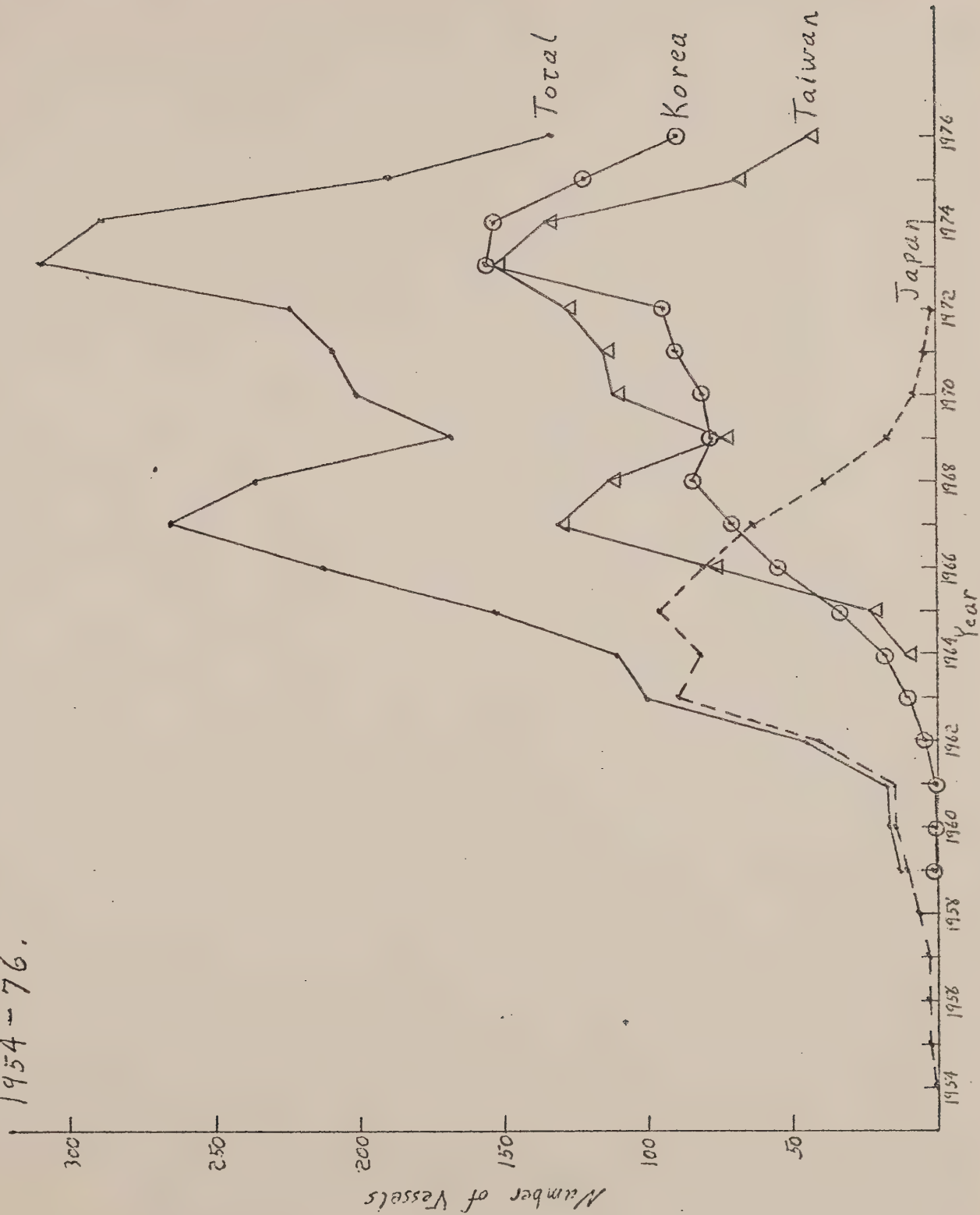


Figure 3. Maximum, mean, and minimum gross tonnage of the longline vessels based in American Samoa, 1954-76.

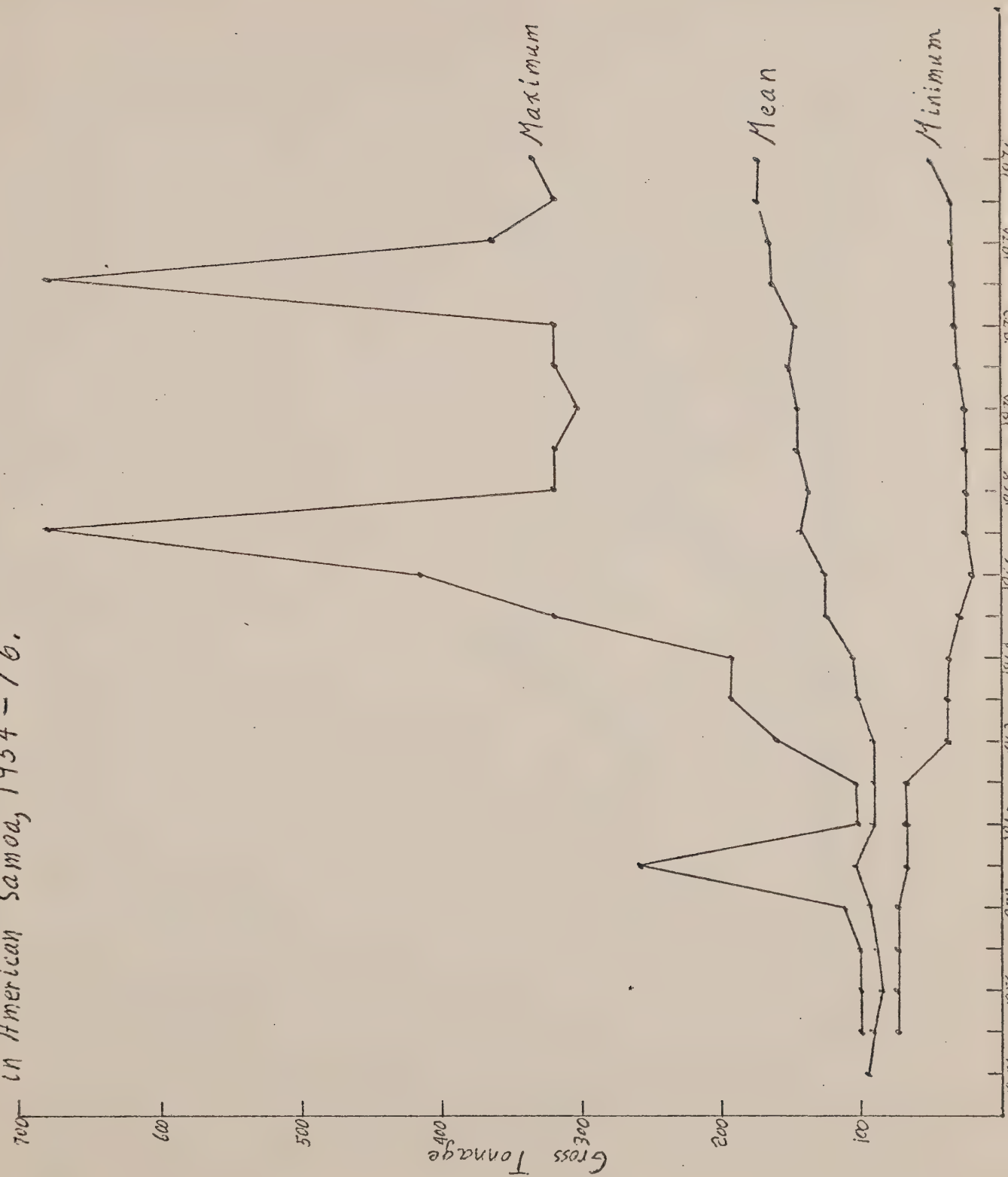


Figure 4. Number of fishing trips by nationality of vessels and by all vessels for the fishery based in American Samoa, 1954-76.

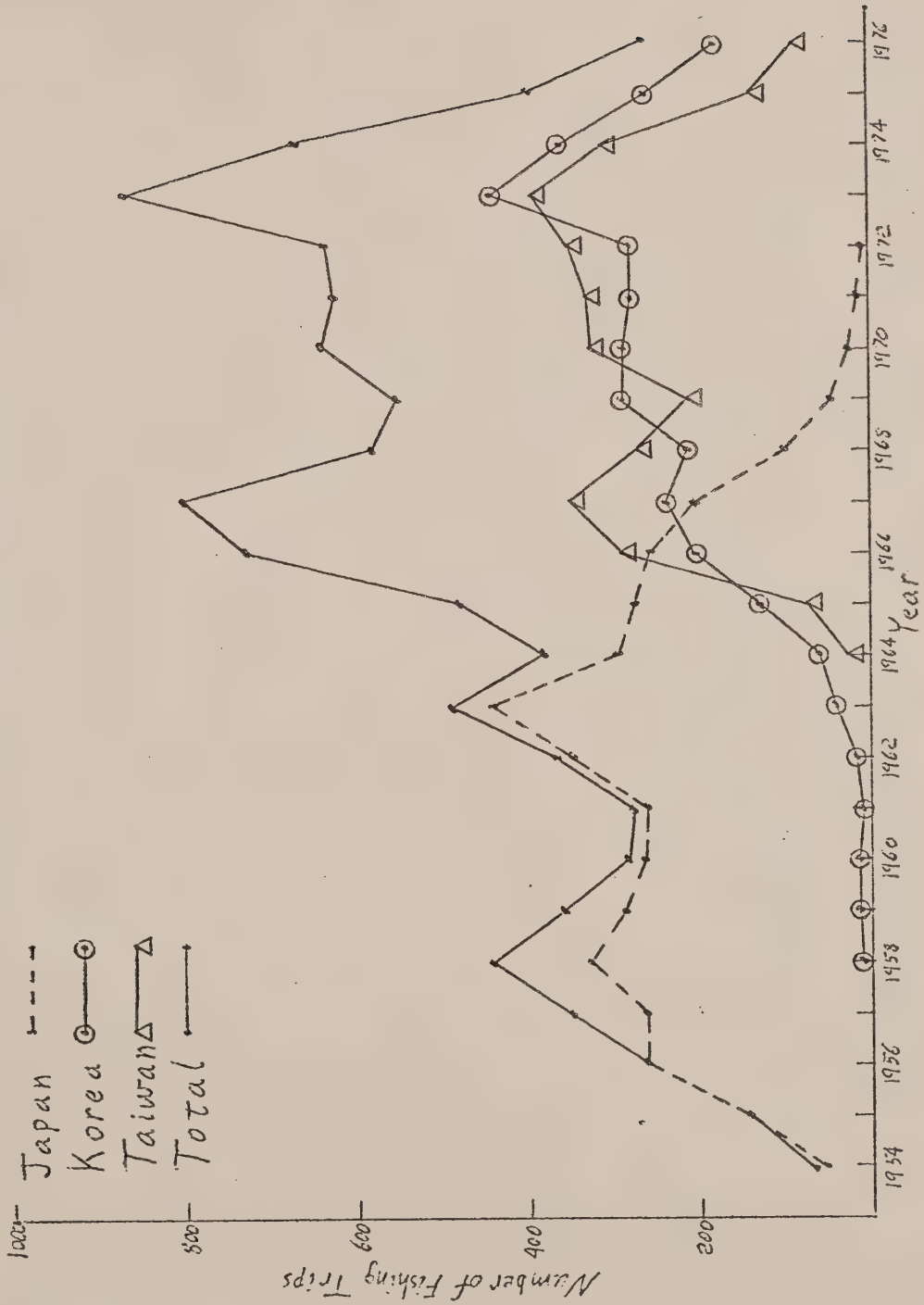


Figure 5. Number of days fished by nationality of vessels and by all vessels for the fishery based in American Samoa, 1957-76.

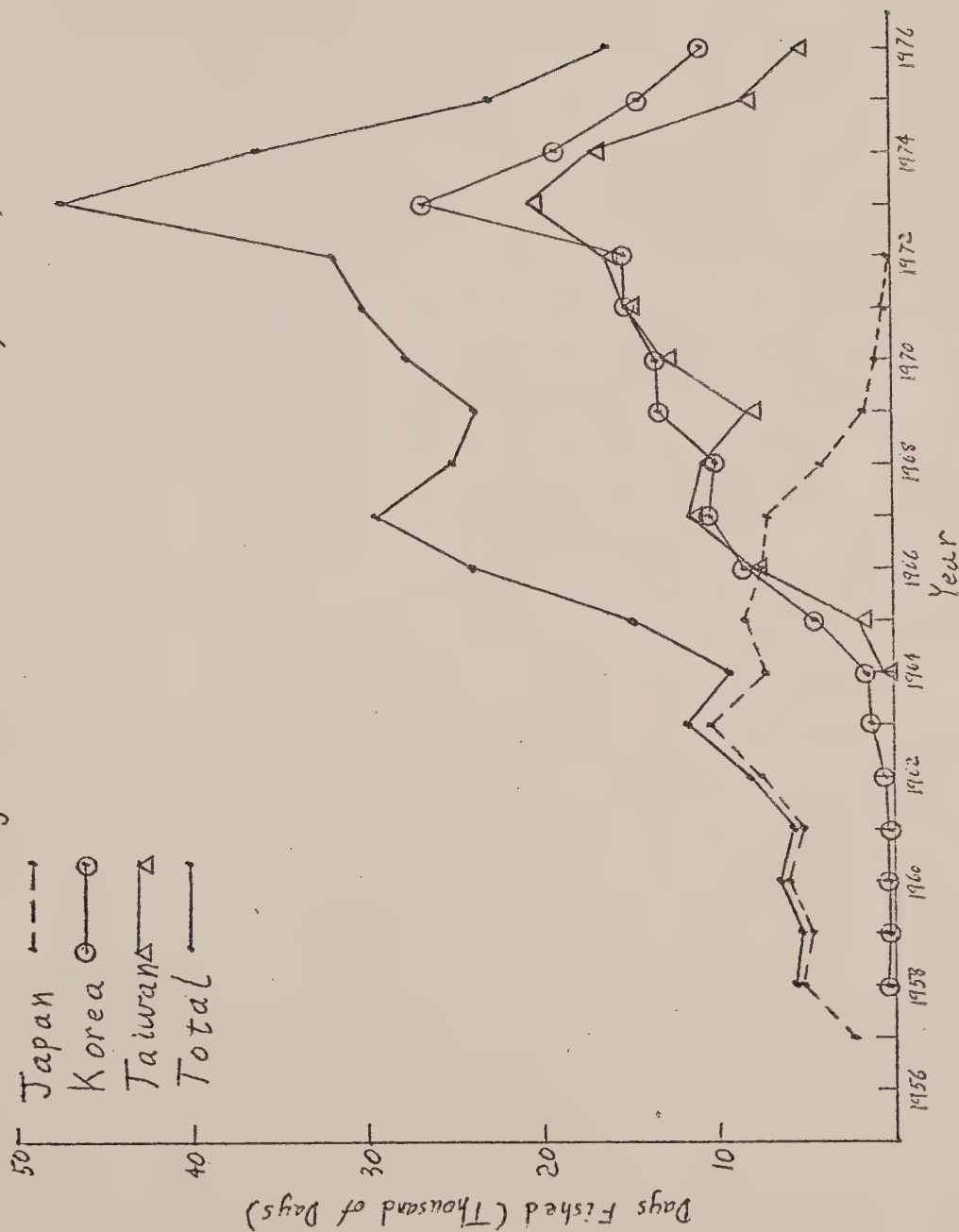
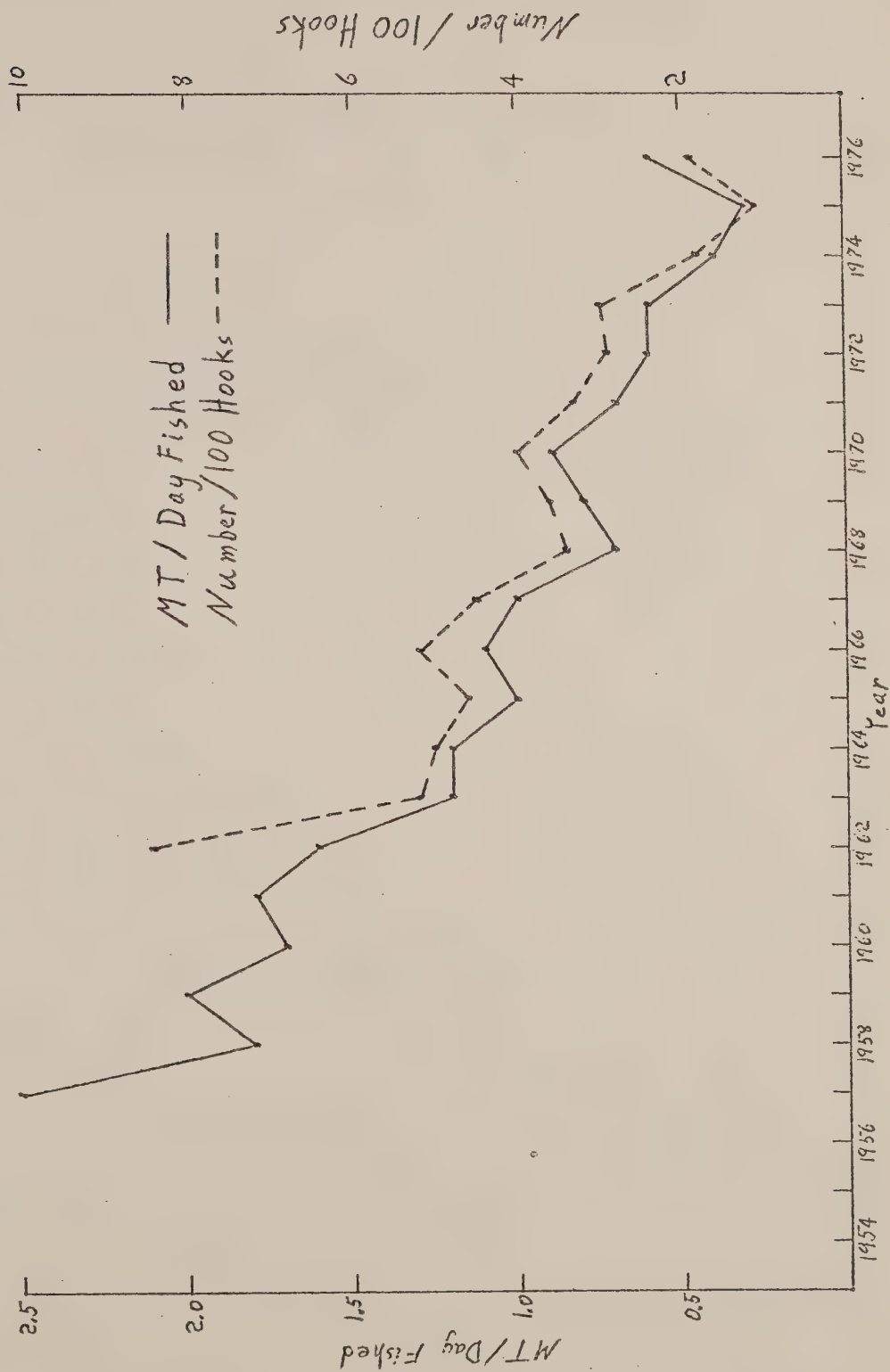


Figure 6. Indexes of relative abundance for the longline fishery based in American Samoa, for albacore.



WHEN THE TWO-PERIOD OPTIMAL POLICY IS OPTIMAL
OVER AN INFINITE HORIZON: A NOTE

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February 1978

DRAFT FOR COMMENT

Problems arising in managing renewable resources, particularly for yield, often take the form:

$$\max E \left\{ \sum_{t=1}^T \alpha^{t-1} P \cdot (x_t - y_t) \right\}$$

$$\text{s.t. } x_{t+1} = s[y_t, D_t]$$

$$0 \leq y_t \leq x_t$$

where x is the state, y is the decision, and the D_i 's are independent, identically distributed random variables. The planning horizon T may be either finite or infinite.

If T is finite, Mendelssohn and Sobel (1977) derive the finite dynamic program:

$$\begin{aligned} f_0(\cdot) &\equiv 0 \\ f_n(x) &= \max_{0 \leq y \leq x} \left\{ P \cdot (x-y) + \alpha E f_{n-1}(s[y, D]) \right\} \end{aligned} \quad (1)$$

and over an infinite horizon:

$$f(x) = \max_{0 \leq y \leq x} \left\{ P \cdot (x-y) + \alpha E f(s[y, D]) \right\} \quad (2)$$

In a series of recent papers (Mendelssohn 1978a, b, c) I show how to greatly reduce the effort involved in solving (2). In this paper, I show that for a special case, an optimal policy in (1) for $n = 2$ is optimal in (2).

Consider the following assumption:

- (i) $f(\cdot)$ is concave, continuous
- (ii) $Es[y, D]$ is unimodal and differentiable with respect to y .

Conditions which are sufficient for (ii) to be valid are given in Mendelssohn and Sobel (1977). Let y_2^* be the solution to the following equation:

$$E\left\{s^{[1]}[y, D]\right\} = \frac{1}{\alpha} \quad (3)$$

Mendelssohn and Sobel (1977) show that both (1) and (2) have a base stock policy as an optimal policy. That is, there is a y^* such that an optimal policy is to choose:

$$\text{minimum } (x, y^*)$$

Clearly y_2^* is the base stock size at $n = 2$. Theorem 1 proves y_2^* is the base stock size in (2) also.

Theorem 1. Assumptions (i)-(ii) imply y_2^* is an optimal base stock size in (2).

Proof. It is straightforward to show that at y^* ,

$$E\left\{s[y^*, D]\right\} \geq y^*$$

(see, for example, Mendelssohn and Sobel 1977).

From equation (1), this implies for $w = E\{s[y^*, D]\}$:

$$f(w) = p \cdot (w - y^*) + \alpha Ef(s[y^*, D])$$

Applying Jensen's inequality yields:

$$p \cdot (w - y^*) + \alpha Ef(s[y^*, D]) \leq p \cdot (w - y^*) + \alpha f(Es[y^*, D])$$

which implies:

$$p \cdot (w - y^*) + \alpha Ef(s[y^*, D]) \leq p \cdot (w - y^*) + \alpha f(w) = p(w - y^*) + \alpha Ef(s[y^*, D]) \quad (4)$$

Equation (4) implies at y^* , $\alpha Ef(s[y^*, D]) = \alpha f(Es[y^*, D])$.

At $y = y_2^*$, $p \cdot (w - y) + \alpha f(w)$ achieves a maximum, which implies $p \cdot (w - y) + \alpha Ef(s[y, D])$ also achieves a maximum at y_2^* . Since a base stock policy is optimal, $y^* = y_2^*$ is the base stock size.

□

What is convenient about theorem 1 is that equation (3) can be solved on nothing more than a pocket calculator. It also underlines a very real problem in using expected value as a criterion for optimization. That is, y_2^* is optimal no matter what the variance of D , so long as the expectation on D is the same. This suggests that when going from deterministic to stochastic models, the expectation of the deterministic objective most likely is not the proper objective function for the stochastic model. There are several ways around this problem. The first is to use utility theory or other related methods to determine the decisionmaker's attitude towards risk. The second is to include smoothing costs of the form:

$$\begin{aligned} & \varepsilon \left((x_{t-1} - y_{t-1}) - (x_t - y_t) \right) \quad \text{if } (x_{t-1} - y_{t-1}) > (x_t - y_t) \\ & \gamma \left((x_t - y_t) - (x_{t-1} - y_{t-1}) \right) \quad \text{if } (x_t - y_t) > (x_{t-1} - y_{t-1}) \end{aligned}$$

In a future paper, I will show that for $\varepsilon = \gamma$, this is equivalent to weighting the mean return against the variance of the return. By parameterizing on ε (therefore γ), it is then possible to explore the mean-variance tradeoff.

I suspect, but have not been able to prove, that if assumptions (i)-(ii) are valid, then a two-period optimal policy to the smoothing cost problem is a good approximation to a true infinite horizon optimal policy. This will be explored numerically.

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RECURSIVE SOLUTIONS TO SOME SEMI-SEPARABLE MARKOV

DECISION PROCESSES: A NOTE

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February 1978

THE PROBLEM OF BURNT TUNA IN THE HAWAIIAN FISHERY

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IN THE IPFC REGION

Manila, Philippines
March 1978

February 1978

¹Part of study done under contract with the Southwest Fisheries Center, National Marine Fisheries Service, NOAA, Honolulu, Hawaii.

Introduction

Tunas represent the most important economic fishery resource in the Hawaiian Islands. In 1976 the total domestic tuna catch was 5,550 metric tons (MT) with an ex-vessel value of \$6.4 million (U.S.). While skipjack tuna, Katsuwonus pelamis, was the most important species in the tuna catch, making up approximately 80% of the landings and 60% of the value, the importance of the other tuna species, especially yellowfin tuna, Thunnus albacares, and bigeye tuna, T. obesus, has increased markedly in recent years. Table 1 provides catch statistics of the tunas for the 1962-76 period. The increase in landings of the combined yellowfin tuna, bigeye tuna, albacore, T. alalunga, and kawakawa, Euthynnus affinis, catch has been due primarily to the expansion of the handline fishery for tunas and the increase in recreational fishing. Recreational fishing in Hawaii has a unique aspect in its operation, wherein the economically valuable species are very often sold through commercial outlets. Basically the operation is still considered recreational fishing since the fishers do not depend upon fishing as a basic means of livelihood.

Economically, the handline fishery for tunas show a potential of tremendous growth if the problem of burnt tuna can be overcome. The present report provides (1) a brief description of the various types of flesh quality problems faced by the tuna industry, (2) a brief description of the handline and troll fisheries in Hawaii, and (3) results of a current study being undertaken by the Honolulu Laboratory (Southwest Fisheries Center, National Marine Fisheries Service) and the University of Hawaii to determine the causative factors involved with burnt tuna and to seek solutions to this costly problem.

Flesh Quality Problems in Tuna

Burnt tuna is raw tuna which is paler and softer than normal. The color may vary from slightly pale (borderline burn) to almost white. The area affected varies from 5% to 100% of the edible meat of the fish. In cases of partial burn the area affected is the part of the meat which is closest to the spinal column. The condition occurs most frequently in large tunas (yellowfin and bigeye) from 45 to 136 kg caught in shallow water. The fish is edible but is less desirable for raw consumption and therefore commands a lower price.

Burnt tuna appears to be similar to a condition in pork known as Porcine Stress Syndrome (PSS) (Hugh 1976). Both conditions involve stress, high body temperatures, acidity of muscle, and result in pale and soft muscles.

Tuna, along with saury, seerfish, butterfly kingfish, and mackerel, normally contain large amounts of free histidine in their muscle tissue. Under certain conditions the free histidine may be decarboxylated by some bacteria to produce high levels of histamine (Geiger 1944; Kimata and Kawai 1953; Ferencik 1970).

Growth of histamine producing bacteria was optimum at acidic pH (5-6) and moderately high temperatures (20°-30°C) (Kimata and Akamatsu 1955).

One of the best methods of retarding bacterial histamine formation in fish is storage below freezing (Brown and Arnold²).

Scombroid fish poisoning clinically resembles histamine poisoning intoxication, however, controversy exists as to whether histamine ingested orally is toxic (Halstead 1967; Granerus 1968; Douglas 1970). A number of reports indicate that histamine taken orally by human subjects is not toxic (Granerus 1968; Douglas 1970; Hardy and Smith 1976). Certain diamines (e.g., putrescine) may alter absorption of histamine (Parrot and Nicot 1965; Irnisteia 1973). Alterations of conditions of the intestinal tract due to consumption of highly seasoned hot dishes or alcohol may cause increased absorption of histamine (Geiger 1955). Whether histamine is the sole toxic factor or not, it is generally found at high concentrations in foods causing scombroid poisoning (Simidu and Hibiki 1955; Ferencik 1970).

Honeycombing is a condition which becomes noticeable after precooking in canned tuna. It is characterized by irregular holes or pits penetrating more or less deeply into the tissue. The size of the honeycombed pits may vary from small pits to pits covering extensive areas. A transverse section of an extensively honeycombed area has an appearance suggestive of an empty honeycomb (Hillig 1956). Fish in this condition are rejected for human consumption.

Otsu (1957) reported that honeycombing in Hawaiian skipjack tuna resulted from delayed refrigeration and was independent of sexual maturity or size of fish. The rate of honeycombing increased with higher seawater temperatures. When allowed to decompose to varying stages yellowfin tuna and skipjack tuna with honeycombing had much higher histamine levels than similar fish without honeycomb (Williams 1954).

Studies presently in progress, however, indicate that honeycombing and histamine production are not interdependent. Fish incubated in the presence of antibiotics exhibit honeycombing but do not have high histamine levels (H. Frank, Department of Food Science, University of Hawaii, Honolulu, Hawaii 96822, pers. commun.)

Green tuna occasionally occurs in precooked tuna when the normal pink color fails to develop. The cooked meat takes on a tannish-green color and is rejected as unsuitable for canning (Brown, Tappel, and Olcott 1958). The pink has been shown to be due to a hemochrome derived from the myoglobin in the loin (Brown and Tappel 1957) and the green is mostly hemichrome (Brown et al. 1958; Naughton, Zeitlin, and Frodyma 1958). The condition does not appear to be related to oxygen starvation during landing (Naughton et al. 1958). Green tuna is most frequently found in yellowfin tuna.

²Brown, W. D., and S. H. Arnold. 1957. Histamine (?) toxicity from fish products. Unpubl. manuscript. Institute of Marine Resources, Department of Food Science and Technology, University of California, Davis, California.

The condition is not recognizable in the raw state and therefore much effort is wasted in processing the fish. Nagaoka, Yamagata, and Horimoto (1971) have developed a method for prediction of green tuna. They report that the determination of trimethylamine oxide and trimethylamine contents in the raw dorsal muscle of yellowfin tuna yields a predictive accuracy of 96%.

Description of Fisheries

The problem of burnt tuna seems to be most serious with tuna caught by trolling, serious with tuna caught on night handlines, and minor with tuna caught on longlines. The problem, in fact, was first brought to the attention of the National Marine Fisheries Service by recreational fishers who troll in the Kona, Hawaii area.

Recreational fishers use rods and reels as fishing gear. They troll lures from a wide variety of boats which range in length from 4 to 18 m. The prime target species are the larger game fish, including yellowfin tuna; blue marlin, Makaira nigricans; striped marlin, Tetrapturus audax; black marlin, M. indica; shortbill spearfish, T. angustirostris; sailfish, Istiophorus platypterus; mahimahi, Coryphaena hippurus; and wahoo, Acanthocybium solandri. Trolling speed is a matter of individual preference and generally ranges from 10 to 20 km/h. Surface water temperatures in the Kona area where the burn problem is most serious vary between 24° and 29°C.

Lines of various sizes are used on the reels. The heaviest line used has a breaking strength of 59 kg or less. Fishers use lighter lines to make fishing more sporting and challenging. Fighting time, the interval between the taking of the lure by the fish and the boating of the fish is highly variable. In the catching of yellowfin tuna, fighting time is partly a function of line strength and fish size. In a sample of 44 yellowfin tuna caught on line with a breaking strength of 36 kg or less, fighting time ranged from 4 to 198 min with a mean of 46 min. The fighting time in a sample of 29 yellowfin tuna caught on line of 23 kg or less breaking strength ranged from 5 to 329 min with a mean of 93 min. Fish in this sample weighed 46.3-115.2 kg. These variables do not account for all of the variability in fishing time. Fishing technique, skill of fishers, vitality of the fish, weather conditions are conceivably other factors.

Another fishery in which burnt tuna is a serious problem is the night handline fishery for tunas. To our knowledge this highly effective method of fishing for tunas is used only on the island of Hawaii and in the Philippines (E. Oswald, South China Seas Fisheries Development and Coordinating Programme, Makati, Rizal, Philippines, 1976, pers. commun.). Until 1976 this method of fishing in Hawaii was limited to a small area off Hilo, Hawaii. Night handline fishers presently fish in areas off the coastline of the entire southern half of the island of Hawaii.

Fishers time their trips to arrive on the fishing grounds at sundown. Upon arrival the engine is shut down and a parachute is attached to the bow and lowered into the water. The parachute is 7.2 m in diameter. Over

surface lights and/or an underwater light are turned on. Typically 25- and 50-W incandescent bulbs are used for the above surface and underwater lights, respectively.

The stage is finally set for fishing with the tossing overboard of a few kilograms of chum consisting of chopped up mackerel scad, Decapterus pinnulatus. If fishing is in an area where the squid, Notodarus hawaiiensis, is expected to be available, then fishing for squid to be used as bait is begun. Otherwise, mackerel scad is used for bait and fishing for tuna commences.

The handline for tuna fishing consists of a hook of Japanese design (Tonkichi BKM No. 54³) at one end attached to a leader of about a meter of 7-strand stainless steelwire of 227-kg (500-lb) test, a lead weight of 227-397 g (8-14 oz), and 110-130 m of line which is usually polypropylene rope either 0.95 cm (3/8 in.) or 0.79 cm (5/16 in.) in diameter. At the start of fishing three handlines are set, one at the bow, one at the stern, and one amidship. As soon as the tuna start biting one line is removed and only two lines are fished. The baited hooks are lowered 20-30 m below the surface and held at that depth by securing the handline to the boat with a restraining line. The restraining line usually breaks when a tuna takes the hook. The restraining line has a breaking strength of about 45 kg (100 lb). This high breaking strength is used to increase the probability that the tuna will be securely hooked when it strikes.

After the restraining line breaks the tuna pulls out the handline at great speed. In a few seconds the drag of the increasing amount of line in the water slows the tuna down. When the outgoing line is slow enough the fisher grabs it and hauls the fish to the boat. When the fish is alongside, it is shot in the head, with either a handgun or bang-stick, hit again on the head with a baseball bat, gaffed, and pulled aboard. The catch is stored in ice or a mixture of ice and seawater.

The fishers leave the fishing ground to arrive at the auction site by 7 a.m. When fishing distant grounds they unload their catches at the nearest landing and truck the fish to the auction market.

The fishery catches bigeye tuna and yellowfin tuna primarily. Albacore is a third tuna species that is commonly caught. The contribution of these species to the handline fishery catch in weight and in value for the years 1973, 1974, and 1975 are listed in Table 2. The catch increased from 89.1 to 154.6 MT during these years, while the value of the catch increased at a slightly faster rate, from \$141.1 to \$327.5 thousand (U.S.).

Although the total tuna catch exhibited a continuous growth for the 3 years, the catches of the individual species fluctuated tremendously between years. In 1974 the bigeye tuna was almost twice as much as the

³Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

other 2 years; in 1975 the yellowfin tuna catch was more than three times the amount of the previous 2 years, and the albacore catch in 1975 increased by fiftyfold.

Serious economic losses due to burnt tuna are incurred by night handline fishers. Rebates on burnt fish were reported to range from 5% to 75% of the original auction price of the fish. Annual loss to night handline fishers due to burnt tuna has been estimated to be as high as 16% of their 1976 catch. Other economic losses include the shipping costs incurred and the inevitable poor reputation that the catch of the night handline fishery engenders due to the inconsistent quality.

Possible Causative Factor in Tuna Flesh Quality

Tunas are unique among fishes in that they are "warm bodied" and excess (above ambient water temperature) body temperatures up to 15°C have been reported. Body temperatures of decked bluefin tuna, *Thunnus thynnus*, were reported to be 5° to 15°C above ambient water temperature (Carey et al. 1971). Dizon, Brill and Yuen (in press) telemetered deep body temperature from free swimming skipjack tuna and found mean body temperatures to be higher than the ambient water temperature. Maintenance of body temperature above ambient water temperature is possible due to the presence of rete mirabile (Carey 1973).

The rete mirabile or "wonderful net" is a tissue composed of closely intermingled veins and arteries which permits the free flow of blood for transport of oxygen and other molecules but impedes the flow of heat from the body tissues to the gills. This conservation of body heat allows the tuna some of the advantages of a homeothermic animal. The higher body temperature increased the speed of metabolic reactions thus making possible a higher maximum swimming speed (Carey 1973). The ability to conserve heat and metabolize rapidly, however, produces the possibilities of overheating and rapid accumulation of metabolic by-products.

These relatively high body temperatures and high metabolic rates may be responsible for meat quality problems such as honeycombing, green tuna, and burnt tuna which are unique to tuna.

Devices to Reduce the Incidence of Burnt Tuna

Fishers have tried various methods to eliminate the burnt tuna condition from developing. Some insist that bleeding the fish before chilling is effective. Others advocate precooling the fish up to an hour by leaving it on deck at night or by placing it under burlap and running seawater over it during the day before placing it in the icebox. No method, however, meets with universal acceptance as the solution to the problem of burnt tuna.

In addition to the fishers' attempts three devices have been made to alleviate the problem. One of them has yet to be tried in Hawaii. Use of the other two has been very limited and, to our knowledge, discontinued.

On the assumption that the burnt condition was caused by improper cooling, the Honolulu Laboratory of the National Marine Fisheries Service distributed for trial a device to hasten the transfer of heat from the warmest part of the fish. The device which had the general shape of a comb consisted of five aluminum baking potato nails (11.7 cm long) held together in a row by an aluminum bar 1 x 1 x 14 cm. Three to five of these were inserted on each side into the dark red flesh that runs longitudinally beneath the lateral line in the section of greatest girth.

After one of the night handline fishers of Hilo tried the device, the others refused to use them. They based their refusal on the following reasons: inserting the devices would require too much time; the bars would not be flush with the body contours and would thus snag and tear the flesh; bacteria would be introduced; and, buyers would not buy fish with holes even if the holes are in flesh that is normally discarded. On the other hand, a small group of fishers in the Kona district have used the device until the supply was depleted due to attrition. Use of the device was reported by one fisher to have decreased the incidence of burnt tuna; this fact has yet to be substantiated.

In November 1975 a Mr. Ogawa of Daiichi Suisan Tsukyi, Japan, demonstrated the use of a metal rod to enhance the chilling of tuna. The demonstration was conducted on the island of Hawaii. The tail of the fish was cut off and a rod approximately 3 mm in diameter was inserted the full length of the vertebral column. The insertion was accompanied by deep incisions immediately posterior to the pectoral girdle and slashing of the gills to bleed the fish. Fishers have resisted using this method because of the work involved.

In September 1977 Mr. Haruyoshi Taniguchi, a recognized tuna expert from Japan, described a tool he has developed to instantly kill tunas. The tool consists of a coring cylinder and a stainless steel wire around which a copper spring is wrapped. The coring cylinder is used to bore a hole into the fish's head at the foramen (whitish spot on the middorsal line just above the eye). A length of wire is inserted through the hole and pushed through the spinal column at least 30 cm. This tool reportedly prevents burnt tuna by quickly destroying the nervous system and thus preventing any further stimulation of physiological activity. This method has not been tested in the Hawaiian Islands (Suisan Sekai 1977).

Study of Causative Factors of Burnt Tuna

A preliminary study was conducted in the fall of 1977 to investigate environmental and physiological factors causing the burnt tuna condition and to investigate the similarities of burnt tuna to PSS in swine.

Data were collected at the Hilo fish auction and on a number of night handline boats. Chilling methods used by individual night handline boats were noted whenever this information was volunteered. The senior author made nine trips on seven different boats. The size of the chill box and pounds of ice on board were recorded for each trip. When a large tuna was caught a blood sample was taken by cardiac puncture and the fish was labeled by clamping an ear tag on the pelvic fin.

Immediately after catching and prior to auctioning the superficial and deep muscle temperatures were taken by inserting an 11 cm probe attached to a telethermometer through the skin of the fish along the midline approximately 11 cm posterior of the pectoral fin. Superficial temperatures were taken at a depth of 1/2 cm and deep temperatures were taken at a depth of 11 cm unless the backbone prevented insertion to that depth. Sex was recorded if the belly was slit and the gonads were exposed at the time of auction. Observations were made of all large tuna which were cut on the auction block. The head and tail were cut off and then the fish were quartered. If burn was present, it was recorded.

Samples of tuna meat were obtained at the Honolulu fish auction. These samples were subsequently classified by the researcher as badly burnt, burnt, or not burnt (normal). Two-gram sections of these samples were placed in 10 ml of distilled water and ground up. The pH of these homogenized samples was then determined. Samples of burnt and normal tuna were assayed for lactate and cultured to determine general bacteria levels.

Samples were also obtained from various parts of a small yellowfin tuna which died during a stress experiment at the Kewalo Research Facility. The pH of these samples was determined using the method described above.

Analysis of variance was used to determine significance of temperature differences between chill techniques and between burnt and normal tuna. The volume of the blood samples collected was not adequate for analysis.

Chill methods

A variety of methods is used to chill fish on the night handline fishing boats. The methods vary in the kind and amount of ice used, mixture of the ice with seawater, location and number of cuts for bleeding, and amount of time the fish is on deck between catching and chilling. Cuts for bleeding were usually at the heart, the belly, or the tail.

Five methods of handling are described in Table 3. Deep and superficial temperatures of all tuna over 45 kg were taken at the Hilo auction from 20 September to 15 October 1977 (Table 4). The superficial and deep muscle temperatures of fish were analyzed to determine if significant differences in temperatures exist between chilling techniques (Table 5). Significant differences in superficial temperatures were found between various chilling techniques. Significant differences, however, were found only in the deep temperatures for two pairs of methods (A and D, C and D). The amount of ice carried is probably the most important difference between methods. Deep temperatures were also affected by the amount of time the fish were kept in the chill box. Fish caught early in the evening have a considerably cooler deep temperature than fish caught in the morning.

No significant differences were found between auction temperatures of burnt and normal fish which were quartered at the Hilo auction (Table 6).

Tissue acidity

The stress of catching may result in acceleration of biochemical activity which will lead to an abnormally low tissue pH, premature rigor mortis, short duration of rigor mortis, and early deterioration of tissue (Borgstrom 1961). Differences in pH of burnt and normal tuna from the Honolulu auction were observed (Table 7). Burnt fish appeared to be consistently more acidic than the normal fish.

Conclusions

Burnt tuna is a system which is the result of two classes of factors, physiological stress and postmortem handling, acting independently or in combination. It appears that physiological stress alone may result in a burnt condition. All methods of chilling including immediate rapid chilling on longline boats result in some percentage of burnt tuna. The burnt condition has been observed immediately after catching (V. Ohai, Oceanic International Corporation, Honolulu, Hawaii 96817, 1977, pers. commun.).

It is not clear whether postmortem handling alone may result in burnt tuna or whether prior physiological stress is a necessary precondition. In any case postmortem handling seems to influence the severity of the condition. High levels of bacteria were found in cultures from both burnt and normal tissue samples. The level of bacterial activity may be affected by handling.

It would be very desirable to create an objective classification system for burnt tuna both from a research and an economic point of view. A color wheel could be developed which would allow an objective classification system for degree of burn of quartered tuna. It may be possible to detect burnt tuna by use of a tissue pH probe. If good correlations are found among the color wheel, visual classification system, and internal pH taken by the probe, a reliable system of grading uncut tuna may be developed.

Further evidence is necessary to confirm that a malignant hyperthermia is involved. It is also possible that an injection of a buffer such as bicarbonate may be used to counteract the effects of stress.

Current efforts in burnt tuna research are concentrated in the following areas: (1) continued investigation of the effects of catching and chilling techniques on the incidence of burnt tuna, (2) investigations into biochemical, histopathological, and microbial differences between normal and burnt tuna immediately after catching and after chilling, and (3) development of an objective classification system for burn in whole uncut tuna.

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Table 1.--Tuna catch, State of Hawaii.

Year	Skipjack tuna		Yellowfin tuna		Bigeye tuna		Albacore		Kawakawa	
	Weight (MT)	Value (thousands of US\$)	Weight (MT)	Value (thousands of US\$)	Weight (MT)	Value (thousands of US\$)	Weight (MT)	Value (thousands of US\$)	Weight (MT)	Value (thousands of US\$)
1976	4,445	3,827	840	1,673	197	825	27	40	41	23
1975	2,293	2,282	781	1,371	157	673	43	83	30	16
1974	3,374	2,676	523	983	187	731	9	15	16	9
1973	4,878	3,203	349	625	185	688	14	28	15	8
1972	4,953	2,949	375	560	229	684	8	12	17	7
1971	6,053	2,753	389	517	214	568	11	11	13	7
1970	3,335	1,497	320	499	216	510	9	11	8	5
1969	2,706	1,245	192	236	322	673	12	12	18	10
1968	4,229	1,540	188	204	256	499	10	8	13	5
1967	3,648	1,263	228	230	294	476	12	9	22	5
1966	4,258	1,404	228	215	346	483	9	6	13	4
1965	7,331	2,014	226	177	351	471	3	2	7	2
1964	4,094	1,222	227	185	380	493	4	3	16	6
1963	3,675	1,090	175	153	430	502	7	5	27	8
1962	4,272	1,174	180	143	554	598	8	4	6	2

Table 2.--Weight and value of tuna catch of night handline fishery.

	Weight (MT)			Value (thousands of US\$)		
	1973	1974	1975	1973	1974	1975
Bigeye tuna	65.4	120.2	63.1	102.6	249.8	149.5
Yellowfin tuna	23.3	22.9	75.5	38.0	38.4	157.0
Albacore	0.4	0.2	16.1	0.5	0.2	21.0
All tunas	89.1	143.2	154.6	141.1	288.2	327.5

Table 3.--Methods of chilling used by handline fishers in Hilo, Hawaii.

Method A - crush ice (not mixed with water)

random cuts for bleeding (few, often none)

5 min on deck between catching and chilling

Method B - 600 lb block ice mixed with seawater

at least two cuts for bleeding

5 min on deck between catching and chilling

Method C - 600 lb block ice mixed with seawater

at least two cuts for bleeding

longer than 5 min on deck

Method D - 300-450 lb of ice mixed with seawater

no cuts for bleeding

5 min on deck between catching and chilling

Method E - 300-600 lb of ice mixed with seawater

random cuts for bleeding

45 min truck ride (without ice) to auction market.

Table 4.--Fish body temperatures ($^{\circ}\text{C}$) at time of auction.

Method	Number of fish	Average superficial temperature	Average deep temperature
A	17	14.9 $\pm$ 0.59	22.74 $\pm$ 1.68
B	44	15.26 $\pm$ 0.61	24.05 $\pm$ 0.77
C	14	17.20 $\pm$ 0.90	21.21 $\pm$ 1.43
D	21	19.50 $\pm$ 0.77	26.61 $\pm$ 0.75
E	6	19.80 $\pm$ 0.51	24.50 $\pm$ 1.82

Table 5.--Comparison of body temperatures by method of chilling
(analysis of variance tests).

Superficial temperature					Deep body temperature				
	B	C	D	E		B	C	D	E
A	0.49	2.30*	4.60**	4.85**	A	1.31	1.53	3.87*	1.76
B		1.94	4.24**	4.49**	B		2.84	2.56	0.45
C			2.30	2.55**	C			5.40**	3.34
D				0.25	D				2.11

* = significant at the 0.05% level

** = significant at the 0.01% level

Table 6.--Body temperature of burnt and normal tuna at time of auction
(20 September-15 October 1977).

	Burnt	Not burnt
Sample size	11	18
Body temperature (°C)		
Deep	25.45 $\pm$ 3.03	25.01 $\pm$ 3.02
Superficial	17.40 $\pm$ 2.13	18.10 $\pm$ 4.11
Average fish weight (lb)	184.64 $\pm$ 35.88	197.94 $\pm$ 79.40
Sex ratio	6 males : 3 females	16 males : 1 female

Table 7.--The pH of tuna sampled at the Honolulu auction.

	All auction samples		Tail		Deep	
	Burnt	Good	Burnt	Good	Burnt	Good
N	17	5	6	1	4	2
$\bar{x}$	5.78	6.12	5.8	6.1	5.76	6.2

TRACKING OF YELLOWFIN TUNA

By

MAY 22 1978

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The Honolulu Laboratory of the National Marine Fisheries Service and the Hawaiian Invitational Allison Tuna Tournament (HIATT) have agreed to jointly embark on the tracking of yellowfin tuna. Mr. Winfred Ho, chairman of HIATT, thought that it would be a good idea for me to inform you, the members of HIATT, of this cooperative research project by writing an article about it for the Official Tournament Program. This article contains a description of the terms of agreement, a brief history of how the agreement came about, a description of the materials and method involved in tracking yellowfin tuna, the objectives of this study, and some noteworthy results from tracking experiments on other game fish species.

Before getting into the subject matter itself I feel it is necessary to explain the scheduling of three events to give you a time context in which to read the article so that you will not be thoroughly disoriented. The deadline for this article to be at the printers was May 15; the tracking was scheduled for June 14-19; and you will probably be reading this article on July 16 at the earliest. So please realize that as I am writing this article the tracking experiment of yellowfin tuna is an event of the future and you are reading it as an event of the past.

In the agreement between Honolulu Laboratory and HIATT, the former will provide the scientific personnel, supplies, and equipment to track yellowfin tuna for 5 days and the latter will charter the *Kamalii Kai Too* for the purpose. The *Kamalii Kai Too*, a 44-ft Striker based in Pokai Bay, was selected because it has the capacity to stay out at sea for 5 days, has living facilities for six people, and is equipped with loran A and a source of electricity to power the scientific equipment. The Honolulu Laboratory will submit a report within 30 days after the conclusion of field work.

The alliance of HIATT and the Honolulu Laboratory on this project originated in the fall of 1975 with a telephone call from Mr. Ho requesting a meeting of representatives from both organizations. At the meeting of Mr. Ho, Senator Kenneth Brown, treasurer of HIATT, Mr. Richard Shomura, director of Honolulu Laboratory, and myself, the HIATT officers offered financial support of research projects of mutual interest. HIATT had done the unthinkable of making a profit on its first two tournaments and wished to rectify that by supporting research.

The solution of the profit problem, like all solutions have a tendency of doing, created a new problem, that of finding a suitable project. The first suggestion was to have a yellowfin tuna tagging event in which a flotilla of recreational fishers would tag and release as many fish as possible when they appeared at the beginning of the season off Kauai. Subsequent recoveries would yield information on the paths and timing of their movements. The possibility that some,

perhaps many, of the yellowfin tuna would not survive the rigors of being caught, tagged, and released made this suggestion even more atrocious than having a profit, however, so the idea was rejected. Tracking was eventually settled upon because it could provide details on behavior and short-term movements that would be of value to recreational fishers and scientists. It could also provide important physiological data and a measure of the survival rate of tagged fish.

Attempts at launching a tracking trip in 1976 failed because no boat owner was willing to have the bulky tracking hydrophone installed on his boat. Since then smaller, streamlined equipment has been acquired, thus making possible the present tracking venture.

The procedure used in tracking a fish involves attaching a small, ultrasonic transmitter on the fish and following the signals of the transmitter with a receiving system mounted on a boat. The transmitter we are using for yellowfin tuna tracking comes in the shape of a cylinder 9.2 cm (3.6 in.) long and 1.6 cm (0.6 in.) in diameter. It is sensitive to pressure and transmits, at a frequency of 50 kHz, pulses at a rate of 60 per min to 150 per min depending on its depth. It has an active life of 3 days.

The receiving system consists of a hydrophone and a receiver. The hydrophone is 20.3 cm (8 in.) wide, 11.4 cm (4.5 in.) high, and 12.7 cm (5 in.) deep. It is mounted on a shaft designed to be versatile enough to be attached to the bow of most small boats. An antenna rotor at the top of the shaft provides scanning capabilities. The signal from the transmitter is detected by the hydrophone and

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relayed to the receiver which converts the 50-kHz ultrasound into audible range. With this system the transmitter can be detected at a range of approximately 3 km (2 miles).

Ancillary equipment have been included in the system to improve measurement accuracy and to make life easier on the scientific observers. A frequency counter provides rapid and precise measurements of the pulse rate. A portable computer and electronic clock are used to automatically record data on a time regimen. The computer is also programmed to convert signal pulse rates to depth readings and periodic position readings from the loran A into speed of travel which, in this case, is a measure of the swimming speed of the tracked fish. An XBT (expendable bathythermograph) unit is used to plot the depth-temperature profile to determine the temperature of the water in which the fish is swimming.

Once preparations have been made and all equipment are checked out, what needs to be done to track a fish is simple. Catch a fish; make a quick judgment on whether or not it is going to survive if released; if so, insert a transmitter and release the fish; listen to the pulses on the receiver and determine the direction they are coming from; when the pulses become faint steer the boat in that direction; and when the pulses become strong, stop the boat. Simple as it is, we do lose contact with the fish on occasion. In fact, the simplicity itself is the major factor in losing fish as tedium-bred carelessness sneaks up on the observer.

The objectives of this tracking trip are; (1) to describe the short-term movements of yellowfin tuna off leeward Oahu; (2) to determine if temperature, salinity, and bottom features influence the movement pattern; and (3) to determine the distance a yellowfin tuna swims over a prolonged period of time. The last objective is part of a study on the energy budget of tunas. In brief, 65% of the energy from a tuna's food intake is available for growth, reproduction, and swimming activity. Data obtained from tracking will make it possible to calculate the amount of energy expended for swimming. Together with information on the energy used for growth and reproduction these data will be used to estimate the rate of energy use and the food requirements to produce that energy. To accomplish the objectives the data collection regime as planned is: time and depth data at 10-sec intervals, position data at 30-min intervals, and temperature-depth profiles and salinity samples at 4-h intervals plus additional observations whenever the scientific observers judge them to be needed.

Fish tracking began a little over 20 years ago with the tracking of salmon in rivers. The tracking of oceanic fish was first attempted in 1969 when we at the Honolulu Laboratory tracked a small aku (skipjack tuna). We have subsequently tracked large aku, albacore, and blue marlin in the Pacific Ocean. Over in the Atlantic Ocean Mr. Donald Merten, a sport fishing enthusiast from New York, has become very interested in tracking game fish. He has equipped his boat with tracking equipment and has invited fishery biologists along

the eastern seaboard to join him in this activity. To date they have tracked sailfish, blue marlin, bluefin tuna, white marlin (a species not found in the Pacific Ocean), kingfish, swordfish, and mako shark.

Much useful information has resulted from these tracks. I shall confine this discussion to the more exciting results, however. Small aku tracked off Kaula Island exhibited a daily pattern of remaining on the bank at the southeast corner of the island all day, going out to sea at night, and, after making a large clockwise circuit, returning to the bank at dawn. Moreover, the night circuit was different on each of the four nights of tracking. Large aku moved freely in a vertical zone between the surface and 270 m during daylight hours. At night they confined their swimming to a zone within 70 m of the surface. Of the three large aku tracked through the late afternoon and early evening within a period of 2 weeks, all of them made the transition from day swimming behavior to night swimming behavior within a minute of 7:45 p.m.! Albacore tracked off the shores of California did not enter water cooler than 15°C (59°F). The albacore also appeared to swim slower when they encountered a temperature front, which is defined as a change in temperature of 0.5°C or larger in a nautical mile. A swordfish that was tracked off Cape Hatteras in the Atlantic Ocean displayed a distinct day and night pattern. During the day it remained close to the bottom at a depth of 400-600 m. At sunset it ascended to the surface and stayed within 20 m of the surface most of the time although it did make excursions to about 200 m. At sunrise it went back to the bottom. On one occasion in 3 days of continuous

observations, it left the bottom and went close to the surface at 2:30 p.m.

As of this writing the outcome of the yellowfin tuna tracking venture is unknown. Whether we successfully track a yellowfin tuna or not, this project marks a milestone in cooperation between a recreational fishing organization and a government organization. I wish to acknowledge the Hawaiian Invitational Allison Tuna Tournament organization for its contribution to game fish research.

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BOUNDS BY DOMINANCE FOR FIXED-WEIGHT AGGREGATED
MARKOV DECISION PROCESSES

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ABSTRACT

Bounds by dominance for aggregated Markov decision processes are developed. These bounds only require the evaluation of K columns as compared to $N \cdot M$ columns, $K < N \cdot M$, and $N \cdot M$ is the total number of actions in all states combined. Separate bounds are given when only actions within a state are aggregated, when states are aggregated only in the rows of the linear programming solution, and for the general aggregate problem. A procedure to tighten the bounds is discussed, and a numerical example is given.

A major deterrent to real world use of Markov decision processes (MDPs) is the large problem size that may arise. For example, some fisheries models may have a seven-dimensional state vector. If only 10 grid points are used in each dimension, the resulting MDP would have 10 million states, and each policy would have a transition matrix too large to calculate even one iteration of successive approximations. Recently, several authors (Hinderer and Hübner [2], White [6], Whitt [7, 8]) have studied the following approach for approximating MDPs: aggregate the states and actions of the original model into a smaller model, solve this aggregated or reduced model, extend the solution of the aggregated model to the original model, and calculate bounds on the loss in value from using this suboptimal policy. These bounds are a posteriori bounds, and require at least the computational equivalent of one iteration of successive approximations on the original model. For problems of similar size as the example above, it would not be practical to calculate the bounds.

In this paper, some results of Zipkin [9, 10] for aggregated linear programming problems (LPs) are used to find a family of bounds that require less computational effort but are looser bounds. These bounds allow the modeler to solve a reduced problem of one size and calculate the bounds on an aggregate problem of a different size, thus allowing the modeler some choice between tightness of the bound and computational effort. A method to improve these "bounds by dominance" is given, and a numerical example is presented where the improved bounds by dominance are almost as tight as the best improved bound, but the computational effort was significantly less.

2. NOTATION

In each period, a state x from a finite set of states is observed, a feasible action y is taken, and a transistion is made to state j with probability $p(x, j:y)$. When state x is observed and decision y is taken, an expected return of $g(x, y)$ is received. The return is discounted through time by a discount factor α , $0 \leq \alpha < 1$.

It is assumed that there are N states, N finite, and without loss of generality, the same M feasible actions per state. It is desired to maximize the expected total return over an infinite planning horizon, and it is assumed that the one-period returns are uniformly bounded from below. This is sufficient to assume that the returns are nonnegative. Given these assumptions, the well known LP solution to this MDP is (d'Epenoux [1])

$$\begin{aligned}
 z^* = \text{maximize} \quad & \sum_{x=1}^N \sum_{y=1}^M g(x, y) u(x, y) \\
 \text{subject to} \quad & \sum_{x=1}^N \sum_{y=1}^M \left(\delta_{xj} - \alpha p(x, j:y) \right) u(x, y) \leq 1 \quad (2.1) \\
 & j = 1, \dots, N \\
 & u(x, y) \geq 0 \quad x = 1, \dots, N; y = 1, \dots, M
 \end{aligned}$$

where $\delta_{xj} = \begin{cases} 1 & \text{if } x = j \\ 0 & \text{if } x \neq j \end{cases}$ and the inequalities in (2.1) are justified

by the nonnegativity of the expected return. Optimal solutions to (2.1) are denoted by u^* , and optimal dual variables by v^* .

The notation and the method of aggregation and disaggregation follows Zipkin [9, 10]. The reader is referred to [9, 10] for more details. Let p be the $N \times N \cdot M$ constraint matrix in (2.1), and let G be the $N \cdot M$ -vector of objective function coefficients in (2.1). Let $\bar{\sigma} = \{\bar{S}_k; k = 1, \dots, \bar{K}\}$ be a partition of $\{1, \dots, N \cdot M\}$, and let $\bar{\rho} = \{\bar{R}_\ell; \ell = 1, \dots, \bar{L}\}$ be a partition of $\{1, \dots, N\}$. Let p^k be the submatrix of p consisting of those columns whose indices are in $\bar{S}_k$, p_ℓ the submatrix whose rows have indices in $\bar{R}_\ell$, and p_ℓ^k the submatrix whose columns and rows have indices in $\bar{S}_k$ and $\bar{R}_\ell$. Let G^k be the components of G whose indices are in $\bar{S}_k$. Let c^k and f^ℓ be nonnegative vectors of appropriate lengths, whose components sum to unity. Then a fixed-weight column aggregated problem, fixed-weight row aggregated problem and doubly aggregated problem are defined by the following transformations:

<u>COLUMN</u>	<u>ROW</u>	<u>DOUBLY</u>	
$\bar{G}^k = G^k c^k$	$p_\ell = f^\ell p_\ell$	$\tilde{G}^k = G^k c^k$	(2.2)
$\bar{p}^k = p^k c^k$		$\tilde{p}_{k\ell} = f^\ell p_\ell^k c^k$	
		$\tilde{p} = (\tilde{p}_{k\ell})$	
		$\tilde{b} = f^\ell \underline{1}$	

These transformations are equivalent to the projection operators in Whitt [7].

The new variables for the column and doubly aggregated problems are denoted by μ , and the new dual variables by ν . Optimal values for the aggregated problem are denoted $\bar{\mu}$, $\bar{\nu}$. For example, the LP for the doubly aggregated problem is:

$$\tilde{z} = \underset{\mu}{\text{maximize}} \quad \sum_{k=1}^K \tilde{G}_{\mu}^k k \quad (2.3)$$

$$\text{s.t.} \quad \tilde{p}_{\mu} \leq \tilde{b}$$

$$\mu \geq 0$$

The solution of the aggregated problem is disaggregated using the identical transformation; for example, if rows are aggregated, then $\bar{v}$ is disaggregated as $\tilde{v}^{\ell} = v_{\ell} f^{\ell}$, where $\tilde{v}^{\ell}$ is a vector with as many elements as in $\bar{R}_{\ell}$. The disaggregated variables will be denoted $\tilde{u}$, $\tilde{v}$. These transformations are Whitt's [7] extension operators.

Let $\sigma = \{S_k: k = 1, \dots, K\}$ and $\rho = \{R_{\ell}: \ell = 1, \dots, L\}$ be any two partitions of $\{1, \dots, N \cdot M\}$ and $\{1, \dots, N\}$ perhaps differing from $\bar{\sigma}$, $\bar{\rho}$. Let $\{d_j\}$ and $\{e_i\}$ be known positive numbers, and $\{w_k\}$ and $\{q_{\ell}\}$ known nonnegative numbers.

Theorem (Zipkin [10]): If it is known a priori that:

$$\sum_{j \in S_k} d_j u_j^* \leq w_k \quad k = 1, \dots, K \quad (2.4)$$

$$\sum_{i \in R_{\ell}} e_i v_i^* \leq q_{\ell} \quad \ell = 1, \dots, L$$

then $\tilde{z} - \epsilon_a^- \leq z^* \leq \tilde{z} + \epsilon_a^+$

where $\epsilon_a^+ = \sum_{k=1}^K \left\{ \max_{j \in S_k} \left[(G^j - \tilde{v} p^j) / d_j \right] \right\}^+ w_k \quad (2.5a)$

$$\epsilon_a^- = \sum_{\ell=1}^L \left\{ \max_{i \in R_{\ell}} \left[(p_i \tilde{u} - 1) / e_i \right] \right\}^+ q_{\ell} \quad (2.5b)$$

Three cases are treated separately in the next section. In the first case, only actions within a state can be aggregated. These partitions of $\{1, \dots, M\}$ will be denoted by $\bar{\sigma}_x = \{\bar{S}_{xk} : k = 1, \dots, \bar{K}\}$ with $\bar{\sigma} = U_x \bar{\sigma}_x$. The second case has columns aggregated as in the first case, but states may also be aggregated in the rows. The third case is the more general doubly aggregated problem.

For any group of partitions $\sigma_x = \{S_{xk} : k = 1, \dots, K\}$ define $G^k(x) \geq \max_{y \in S_{xk}} G(x, y)$ and $p^k(x, j) \geq \max_{y \in S_{xk}} p(x, j:y)$. Let $\{d_{xk}\}, \{w_{xk}\}$ be the obvious redefinitions of $\{d_k\}$ and $\{w_k\}$. The results of this paper utilize the fact that $G^k(x)$ and $p^k(x, j)$ can be used to simplify (2.5). The original bounds (2.5), like the bounds in Whitt [7], at least require evaluating one iteration of successive approximation. The new bounds do not, but with an obvious loss of value.

3. RESULTS

Only the proof for the first theorem will be given in detail, since the proofs of the other theorems are similar. The main result used is the fact that " $\max \Sigma \leq \Sigma \max$." Theorem 3.1 gives the equivalent bound by dominance to (2.5a).

Theorem 3.1 If only actions within a state are aggregated, let z^*
be the value of a solution to the original LP and $\tilde{z}$ the value of a
solution to the aggregated LP, then:

$$\tilde{z} \leq z^* \leq \tilde{z} + \epsilon_+$$

where

$$\epsilon_+ = \sum_{x=1}^N \sum_{k=1}^K \left\{ \left[G^k(x) + \alpha \sum p^k(x, j) \tilde{v}_j - \tilde{v}_x \right] / d_{xk} \right\}^+ w_{xk} \quad (3.1)$$

Proof. The theorem would be true if for each of the $N \cdot K$ columns in the aggregate problem:

$$G^k(x) + \alpha \sum p^k(x, j) \tilde{v}_j - \tilde{v}_x \geq \max_{j \in S_{xk}} \left\{ G(x, y) + \alpha \sum p(x, j:y) \tilde{v}_j - \tilde{v}_x \right\}$$

However, the result is immediate from the definition of $G^k(x)$, $p^k(x, j)$.

□

The bound (3.1) requires the evaluation of $N \cdot K$ inner products between two N -vectors, while (2.5a) requires the evaluation of $N \cdot M$ inner products between two N -vectors. For N large and $K \ll M$, the computational savings is substantial. A likely procedure would be to choose $\bar{K} \leq K \ll M$. Note also that the values of $G^k(x)$, $p^k(x, j)$ need not be found by sorting through the constraint matrix, but can be well chosen values based on knowledge of the problem.

If states are aggregated together only in the rows, then the upper bound in theorem 3.1 remains valid. However, the lower bound must be altered. Define $p_\ell(x:y) = \min_{j \in R_\ell} p(x, j:y)$, $e_\ell = \min_{j \in R_\ell} e_j$ and for each $j \in R_\ell$, $\tilde{u}(j) = \sum_{y=1}^M \tilde{u}(j, y)$. For most usefully aggregated problems, only

one value of $\tilde{u}(j, y)$ will be nonzero. Then let $\tilde{u}_\ell = \max_{j \in R_\ell} \tilde{u}(j)$.

Theorem 3.2 The assumptions of theorem 3.1, plus states being aggregated in the rows only, imply

$$\tilde{z} - \epsilon_- \leq z^* \leq \tilde{z} + \epsilon_+$$

where
$$\epsilon_- = \sum_{\ell=1}^L \left\{ \left[\sum_{x=1}^N \sum_{g=1}^M \left[u_{\ell} - \alpha p_{\ell}(x:y) \tilde{u}(x, y) - 1 \right] / e_{\ell} \right] \right\}^+_{q_{\ell}} \quad (3.2)$$

□

The bound in theorem 3.2 involves evaluating L inner products between two $N \cdot M$ -vectors, while (2.5b) requires evaluating N inner products between two $N \cdot M$ -vectors. For $N \cdot M$ large and $L \ll N$, this is a substantial saving. Both theorems 3.1 and 3.2 require that the optimal solution or optimal dual variables be disaggregated, and that the upper (resp. lower) bounds $G^k(x)$, $p^k(x, j)$ (resp. $p_{\ell}(x:y)$) be based on the original problem. In fact, it is not necessary to totally disaggregate the final solution of the aggregate LP, and the bounds can be based solely on the partially aggregated tableau. This is proven for the upper bound in theorem 3.2. The lower bound is proven similarly.

Define $\bar{p}(x, \ell:y)$ as the aggregate probability of going from state x to the new row-aggregate state ℓ when action y has been taken. And let

$$\bar{p}^k(x, \ell) \geq \max_{y \in S_{xk}} \bar{p}(x, \ell:y).$$

Theorem 3.3 The assumptions of theorem 3.2 imply $z^* \leq \tilde{z} + \epsilon_+^2$

where
$$\epsilon_+^2 = \sum_{x=1}^N \sum_{k=1}^K \left\{ \left[G^k(x) + \alpha \sum_{\ell} \bar{p}^k(x, \ell) \bar{v}_{\ell} - \tilde{v}_x \right] / d_{xk} \right\}^+_{w_{xk}} \quad (3.3)$$

$$\begin{aligned}
\text{Proof. From (2.5a), } & \sum_{k=1}^K \left[g(x, y) + \alpha \sum_j p(x, j:y) \tilde{v}_j - \tilde{v}_x \right] \\
&= \sum_{k=1}^K \left[g(x, y) + \alpha \sum_{\ell} \sum_{j \in R_{\ell}} p(x, j:y) (\bar{v}_{\ell} f_{\ell}^j) - \tilde{v}_x \right] \\
&= \sum_{k=1}^K \left[g(x, y) + \alpha \sum_{\ell} \bar{v}_{\ell} \sum_{j \in R_{\ell}} p(x, j:y) f_{\ell}^j - \tilde{v}_x \right] \\
&= \sum_{k=1}^K \left[g(x, y) + \alpha \sum_{\ell} \bar{p}(x, \ell:y) \bar{v}_{\ell} - \tilde{v}_x \right]
\end{aligned}$$

The rest of the proof is the same as the proof of theorem 3.1.

□

The bound in theorem (3.3) requires evaluating $N \cdot K$ inner products between two L -vectors instead of two N -vectors. For $L \ll N$, the increased savings in computational effort is significant. If states are to be aggregated in the columns also, it is reasonable to assume that an aggregate would be formed by aggregating the same actions between states to produce a new aggregate state with M action but with aggregate transition probabilities, and then to further aggregate the actions within the aggregate state. Let $\sigma = \{S_k : k = 1, \dots, K\}$ be a partition of $\{1, \dots, N\}$, and S_k index the states that have been (column) aggregated together. Let $\tilde{v}_k = \min_{x \in S_k} \tilde{v}_x$. Then theorem 3.3 extends to the more general aggregation scheme by substituting $\tilde{v}_k$ for $\tilde{v}_x$ in (3.3)

4. EXTENSIONS AND EXAMPLES

In Mendelssohn [4], a method of Kallio [3] is used to improve all of the bounds discussed in this paper. This is done by including the constraints (2.4) directly into the LP (2.1), and also adding the additional constraint that the vector of variables u must lie in the set $U = \{u \mid u = \theta u, \theta \in R\}$. This additional constraint produces a parametric family of values $z^*(\theta)$ and a parametric family of bounds. At $\theta = 1$, the bounds are equivalent to the original bounds. A search procedure is used to find the value of θ that produces the smallest bound.

I, II It has been shown mathematically that the bounds by dominance require significantly less computation; it would be hoped that this is without a concomitant loss in the tightness of the bound. As an example, a model suggested by Mathews [11] for salmon runs in the Naknek River is analyzed. The "original" problem has a state space of 31 points lying between 0 and 7 million fish. The aggregate problem and its solution are presented in Table I, and Table II gives the variable definitions, the stochastic transistion function, and four different error bounds calculated from this example.

As can be seen in Table II, the bounds by dominance are not tight at all, but the improved bounds by dominance are almost as tight as the best available bound. One example does not imply that improved bounds by dominance will always, or even often, provide tight bounds. However, the example shows that they can provide tight bounds while requiring significantly less computational effort; further computational work needs to be performed on real life models to study the behavior of these bounds.

A more intriguing question, which has not been examined at all, is if any of the bounds are monotone in the sense that a tighter bound implies that the expected value of the extended policy on the original model is greater. Such monotonicity properties would provide clear guidelines for modeling. Finally, the Russian literature over the last decade or so has studied processes that iteratively aggregate using the extended solution from the previous aggregate problem to reaggregate the model (see Vakhutinsky, Dudkin, and Ryvkin [5] and references therein). A combination of iterative aggregation combined with bounds to guide the reaggregation process would appear to be a fruitful area of future research.

ACKNOWLEDGMENTS

I am grateful to Profs. M. J. Sobel and P. Zipkin who shared with me many of their unpublished ideas for approximating MDP's; this paper is an outgrowth of those discussions. The associate editor and a referee provided numerous suggestions that greatly improved the content of this paper.

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TABLE I
Aggregated LP for Naknek salmon

Partition	Variables in the partition	Weighting for aggregation	Upper bound P_k
1	$\{u_x^0, u_x^{0.125}; x \in X\}$	Zero on u_x^0 1/30 on $u_x^{0.125}$	35
2	$\{u_x^{0.25}; x \in X\}$	1/29 on each column	10
3	$\{u_x^{0.375}; x \in X\}$	1/28 on each column	10
4	$\{u_x^{0.5}; x \in X\}$	1/27 on each column	10
5	$\{u_x^{0.625}; x \in X\}$	1/26 on each column	10
6	$\{u_x^{0.75}; x \in X\}$	1/25 on each column	1,000
7	$\{u_x^{0.875}; x \in X\}$	1/24 on each column	10
8	$\{u_x^1; x \in X\}$	1/23 on each column	10
9	$\{u_x^{1.125}; x \in X\}$ and $\{u_x^y; 9 \geq x \geq 1.125;$ $1.25 \leq y \leq x; x, y \in X\}$	1/22 on each column Zero on each column	10

$$G^k(x, y) = \{9, 8.75, 8.625, 8.5, 8.375, 8.25, 8.125, 8, 7.875\}$$

$$P^k = \{1, 0.7, 0.7, 0.41, 0.7, 0.7, 0.7, 0.7, 0.7, 0.2, \\ 0.7, 0.7, 0.7, 0.7, 0.7, 0.25, 0.7, 0.7, 0.7, 0.7, \\ 0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7, \\ 0.7\} \text{ for all } k = 1, \dots, K.$$

The optimal dual variables for the aggregated LP are:

$$\bar{f} = \{0, 0, 321.0216, 92.4958, 0, 0, 0, 0, 0, 179.4263, \\ 0, 0, 0, 0, 0, 31.3039, 0, 0, 0, 0, 0, 0, 0, 0, 0, \\ 0, 0, 0, 0, 0, 0\}$$

TABLE II

Example of the Different Bounds

Model: Salmon runs in the Naknek River:

x_t = Number of fish that return to river at time t

y_t = Number of fish released to spawn at end of time t

$x_t - y_t$ = Catch = One-period return

$x_{t+1} = 6.727 \exp(d) y_t \exp\{-0.859 y_t\}$

$d \sim N(0, 0.1444)$

Original problem has 31 states, $z^* = 1918.1672$

Regular bounds

Bounds by dominance

Improved bounds

Improved bounds
by dominance

$624.25 \leq z^* \leq 14,849.09$ $624.25 \leq z^* \leq 347,663$ $624.25 \leq z^* \leq 9,051.62$ $624.25 \leq z^* \leq 9,147.00$

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SEAMOUNT FISHERY, FOREIGN VESSEL OBSERVER REPORT
RYUYO MARU NO. 2 (APRIL 22-JUNE 3, 1978)

By

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June 1978

The Ryuyo Maru No. 2 was chartered by the Japan Marine Fishery Resource Research Center (JAMARC) to survey the seamount resources, particularly those of southeast and northwest Hancock which lie within the contiguous fishery zone of the United States. This charter was the second survey conducted by JAMARC to assess the central North Pacific seamounts.

JAMARC is a semi-governmental organization that operates with funds provided half by the Japanese Government and half by the fishing industry to develop and promote existing and latent fishery resources. JAMARC's research covers both the scientific and commercial aspects of fisheries.

Vessel Statistics

Permit No.: JA-78-0330	Vessel type: Independent stern trawler
Length: 91.6 m	Width: 15.5 m Draft: 6.5 m
Gross tonnage: 2,961.07	Net tonnage: 1,501.27
Engine type: Diesel	Horsepower: 4,000
Hull No.: 100883	Registration No.: TK 1-837
Year commissioned: 1967	Radio call sign: JGYV
Company: Hokaido Gyogyokosha	
Home port: Tokyo Harbor	

Personnel

Captain: Osamu Mishima	No. officers: 10
	No. crew: 40
	Engineers: 6
	Galley: 4
	Deck and processing: 30

Observer for JAMARC: Yutaka Niimi
Total ship complement: 52
Experience in seamount fishery: No prior experience

Trawl Gear

See attachment 1 for dimensions. The net was modified by replacing the center bobbins with used car tires to reduce "hangups."

Operations

<u>Seamounts trawled</u>	<u>Lat.</u>	<u>Long.</u>
Hawaii-FCZ 80:		
SE Hancock	29°43'-49'N	179°02'-06'E
NW Hancock	30°15'-16'N	178°42'-44'E
Seamount at	30°22'N	177°33'-35'E
Colahan	31°00'-02'N	175°54'-55'E
Kanmu	32°14'-15'N	172°44'-52'E
Kinmei	35°12'-28'N	171°26'-31'E

Target Species

Common names: Pelagic armorhead, kusakari tsubodai
Scientific name: Pentaceros richardsoni
Species code: 080

Common names: Alfonsin, kinmedai
Scientific name: Beryx splendens
Species code: 081

TRAWL RESULTS

The general fishing strategy involved the use of two fish finders to locate concentrations of fish over suitable trawling grounds. In most instances, the trawl set was commenced prior to contact with the seamount. During trawl operations the net recorder was monitored continuously for depth of trawl, "hangups," and density of fish entering the net. Trawling was generally conducted on the bottom or within a few meters off the bottom.

The net was fished for an average of 26.8 min/tow on SE Hancock and 8.6 min/tow on NW Hancock. Hauls on seamount at lat. 30°22'N, long. 177°33'-35'E averaged 5 min/tow; Colahan, 12.5 min/tow; Kanmu, 17.1 min/tow; and Kinmei, 51.7 min/tow.

Of the total 459.9 metric tons (MT) of fish caught during the survey, 431.9 MT, or 94% consisted of pelagic armorhead (Table 1). Alfonsin comprised 18.0 MT or 4% of the catch. Other fishes of diverse species were taken in small quantities (Table 2). Of the total catch, 90% (416.4 MT) was caught within the FCZ.

The largest single catch inside of the FCZ was 38.7 MT. Of the 101 trawl tows on the Hancock seamounts, 32 produced catches greater than 3 MT and 41 hauls resulted in catches below 3 MT. There were 28 zero catch hauls.

Night hauls accounted for 90% of the armorhead catch in the FCZ. Sixty-nine percent of the total catch was caught between 1800 and 2359 h, 21% between 0000 and 0559 h, 8% between 0600-1159 h, and 2% between 1200 and 1759 h.

The first 4 days of trawling on SE and NW Hancock produced 82% (340.5 MT) of the total catch from the Hancock seamounts. Because of the steady decline in catches, 4 days were spent trawling outside of the FCZ. The CPUE remained poor even after the "cooling off period." The largest single catch outside of the FCZ was 10.8 MT. Of the 54 tows conducted, 26 hauls resulted in catches below 3 MT and 24 hauls produced zero catches.

SAMPLING RESULTS

A. Pelagic armorhead

1. Morphology

Pelagic armorheads caught consisted of two body forms: "fat" and "lean" types. Because of the possibility that the two body types may have ecological significances, they were recorded separately.

a. Hancock seamounts

The average catch composition was 98% "lean" type.

"Lean" type:

No. measured: 1,625

Sex ratio: Females 301--61%

Males 190--39%

Average length 29.3 cm. Size range 25.0-34.0 cm.

Average weight 0.38 kg.

"Fat" type:

No. measured: 81

Sex ratio: Females 31--57%

Males 23--43%

Average length 30.2 cm. Size range 27.2-33.2 cm.

Average weight 0.65 kg.

Number of otoliths taken: 62. Size range 24-34 cm.

b. Colahan seamounts

The average catch composition was 63% "lean" type.

"Lean" type:

No. measured: 256

Average length 30.3 cm. Size range 27.6-33.8 cm

Average weight 0.52 kg.

"Fat" type:

No. measured: 151

Average length 31.3 cm. Size range 27.2-34.3 cm.

Average weight 0.69 kg.

Number of otoliths taken: 6. Size range 27-33 cm.

c. Kinmei seamounts

Only "lean" type armorhead was caught on this seamount.

No. measured: 22

Average length: 35 cm. Size range 29.5-38.2 cm.

Average weight: 0.69 kg.

Number of otoliths taken: 13. Size range 29.5-38.2 cm

2. Food and feeding habit

The principal food items found in the stomach contents of armorhead caught on the seamounts were: copepods, amphipods, euphausiids, shrimps, salps, myctophids, and small fishes. Stomach volume and condition of contents suggest that feeding took place only during the day and that feeding peaks occurred in the morning and late afternoon.

3. Gonad condition

Gross examination of ovaries indicated that the majority of females were in the early developing stage of maturation.

B. Alfonsin

Alfonsin was taken incidental to pelagic armorhead and generally made up only a small portion of the total catch (Table 2). This species was caught in only 29 of the 155 hauls conducted during the survey. The largest haul of 7.3 MT was made on Colahan seamount. Only two hauls on Hancock produced catches greater than 400 kg.

The sizes of alfonsin caught appear to vary from location to location (Table 3). Because of the variation in sizes and limited sampling, no analysis was conducted. The data, although limited, suggest that the trawl was selectively catching small alfonsin.

A total of 109 otoliths was extracted from 14.1 to 49.5 cm fish for aging.

C. Approximately 300 g of black coral, Antipathes sp., and 500 g of bamboo coral, Keratoisis nuda, were dredged up while trawling on Kinmei seamount. No precious coral was found on Hancock.

SHIPBOARD PRODUCTS Hancock seamounts

A. Species product

1. Pelagic armorhead	Frozen fish (headed and gutted)	246.7 MT
	Fish meal and oil	--

a. Frozen fish

The body of the "lean" type armorhead averaged 58% of total fish weight after hand processing (heading and gutting). Recovery of machine cut fish was estimated at 50% of total fish weight.

The body of "fat" type armorhead averaged 63% of total fish weight after hand processing.

2. Alfonsin	Frozen whole	2.0 MT
	Fish meal and oil	--
3. Others	Frozen whole	3.7 MT
	Fish meal and oil	--

B. By-products

Reduction of raw product (head, viscera, and whole fish) was estimated at 164.0 MT, for fish meal, 43.155 MT, and oil, 45.5 kl or a ratio of approximately 3.8:1:1, for the total catch. The daily reduction could not be determined because of "carry-over" in raw product from the previous day's catch.

ITINERARY

Departed Honolulu	April 19, 1978 (1315)
Arrived in Japan	April 20 (1600) +19 h
Aboard vessel	April 22
Port of departure	Tokyo Harbor
Departed	April 22 (1500)

Date sampling began	May 1, 1978
Date sampling ended	May 27, 1978
Total No. days sampled	27

Port of return	Chiba, Japan
Date of return	June 3, 1978 (1000)

Departed Japan	June 10, 1978 (2200)
Arrived in Honolulu	June 10, 1978 (0945)

RECORDS

The following records were kept:

Daily Trawl Haul Form
Size Frequency Log
Production Log

OBSERVER

Thomas K. Kazama - National Marine Fisheries Service, Honolulu
Laboratory

Table 1.--Trawl catches in metric tons by species and area.

Species	Area	
	Hawaii-FCZ 80	Outside
Armorhead	407.1	24.8
Alfonsin	3.7	14.3
Others:	5.6	4.4
	<u>Erythrocles schlegeli</u>	
	<u>Antigonia eos</u>	
	<u>Chlorophthalmus oblongus</u>	
	<u>Ariomma lurida</u>	
	<u>Zeus nebulosa</u>	
	<u>Macrorhamphosus gracilis</u>	
	<u>Polymixia japonica</u>	
	<u>Priacanthus boops</u>	
	<u>Grammatonotus laysanus</u>	
	<u>Hollardia goslinei</u>	
	<u>Decapterus russelli</u>	
	<u>Collybus drachme</u>	
	<u>Scomber japonicus</u>	
	<u>Chascanopsetta prorigera</u>	
	<u>Promethichthys prometheus</u>	
	<u>Ruvettus pretiosus</u>	
	<u>Etmopterus villosus</u>	
	<u>Squalus fernandinus</u>	
	Moridae	
	Coryphaenoididae	
	Congridae	
Total	416.4	43.5

Note: Checklist incomplete, pending identification of specimens.

Table 2.--Catch-per-unit-effort by species and area.

Area	No. hauls	Total min.	Armorhead		Alfonso		Others		All species	
			Total catch (kg)	Kg/min	Total catch (kg)	Kg/min	Total catch (kg)	Kg/min	Total catch (kg)	Kg/min
SE Hancock	62	1,662	228,800	137.66	2,400	1.44	3,800	2.29	235,000	141.39
NW Hancock	39	335	178,300	532.23	1,300	3.88	1,800	5.37	181,400	541.49
30°22'N 177°33'-35'E	4	20	100	5.00	0	--	0	--	100	5.00
Colahan	30	375	24,200	64.53	10,400	27.73	300	0.80	34,900	93.07
Kanmu	7	120	0	--	400	3.33	0	--	400	3.33
Kinmei	6	310	100	0.32	3,500	11.29	4,100	13.22	7,700	24.84
Total	148	2,822	431,500		18,000		10,000		459,500	

¹First seven tows omitted. Total catch 400 kg armorhead.

Table 3.--Size range of alfonsin caught by area.

Area	Haul No.	Sample size	Size range (cm)	Average length (cm)
SE Hancock	20	72	15.4-23.2	20.26
NW Hancock	48	40	27.0-37.5	32.18
	50	27	15.5-24.3	18.70
	53	20	27.3-39.8	--
	64	66	16.4-22.0	19.17
Colahan	89	80	15.3-23.5	19.57
	195	100	16.2-23.6	20.95
	131	100	15.0-21.2	16.68
	139	90	15.3-22.0	18.78
Kinmei	154	100	15.5-33.0	27.47

Vessel Type Independent Stern Trawler

Observation Period
Trawling period

April 22 to June 3, 1978
May 2 to 21

Trawl Doors: Shape Rectangle

Type Concave

Dimensions 4.3 m. x 2.7 m.

Weight 4167 kg

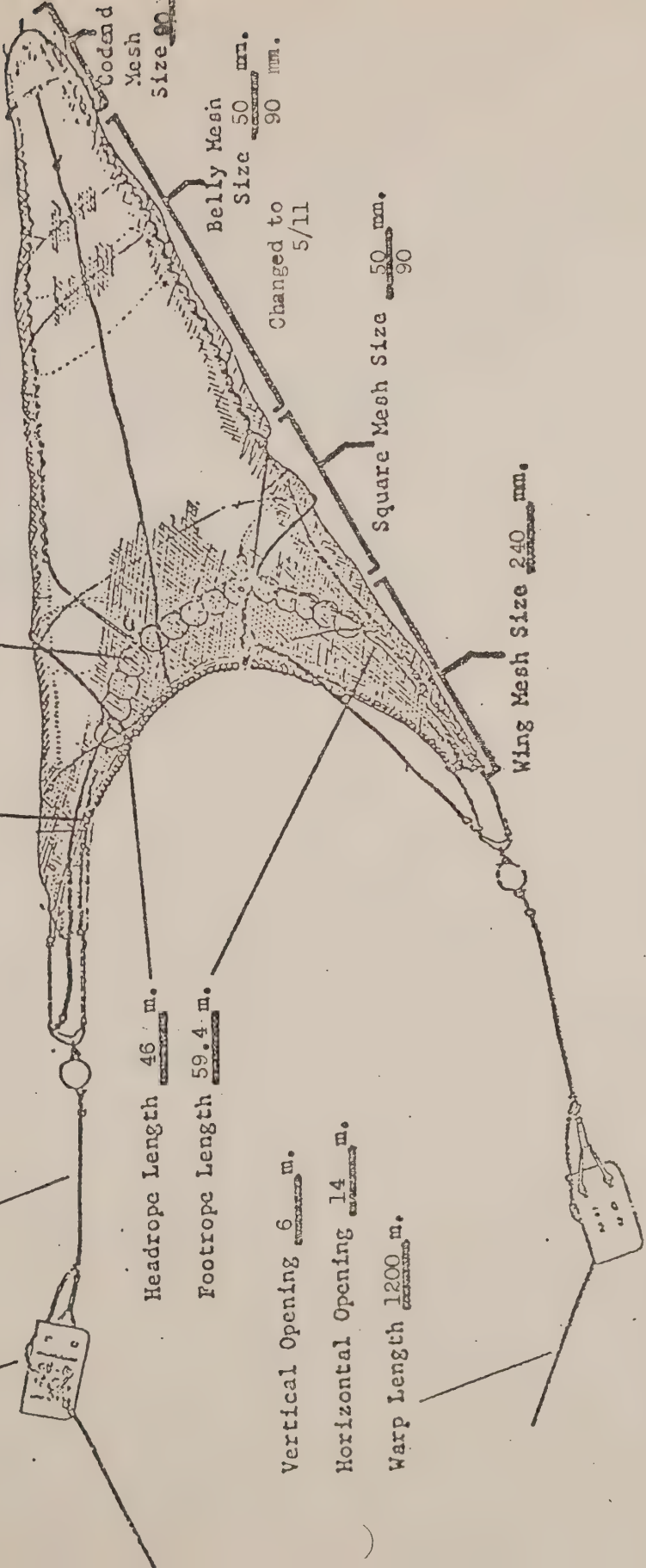
Dandyline Length 150 m.

Center bobbins:
104 car tires

Bobbins: Number 36
Size 36 cm.
Material Plastic
Shape Round

Bobbins: Number 10
Size 54 cm.
Material Steel
Shape Round

Rubber



Fish Finder

Name Furuno
Model Number FTG 422A
Frequency 28 & 50 kHz

Net Recorder

Name Furuno
Model Number FNR-200, Mark II
Frequency AC 100V 60 Hz

IMPROVED BOUNDS FOR AGGREGATED LINEAR PROGRAMS

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July 1978

DRAFT FOR COMMENT

ABSTRACT

A method of Kallio for improving bounds on the optimal value of a linear program calculated from an intermediate iteration is used to improve Zipkin's bounds for an aggregated linear program. The method is also extended to obtain improved bounds for aggregated Markov decision problems, including improved bounds by dominance. Both theoretical and computational results are given, demonstrating the improvement due to these new bounds.

I. Introduction

One method for solving large scale linear programs (LPs) or large scale Markov Decision Processes (MDPs) is to aggregate the original LP into a smaller LP, solve the smaller LP, disaggregate the solution to the smaller LP back into the original tableau, and put bounds on the difference between the true optimum and this approximate optimum. Zipkin [5] has studied this problem extensively where the columns or rows or both are aggregated and disaggregated either by fixed weights, by "optimal" disaggregation, or else by dominance. For each of these problems, Zipkin gives upper and lower bounds for the value of a true optimum.

In related work, Kallio [2] derives bounds for a nonaggregated LP which is stopped at some iteration of the simplex method, using the primal and dual variables of the LP tableau at the stopped iteration. Then Kallio shows how to use marginal analysis to tighten the original bounds, using significantly less computation than would be required to perform one further iteration of the simplex method.

For a nonaggregated LP, Kallio's theorem 1 and Zipkin's proposition 2 are identical. Theorem 2.1 of this paper shows that Kallio's method of tightening the bounds extends readily to an aggregated LP. Theorem 3.1 demonstrates that Kallio's method also extends to discounted, infinite horizon MDPs that are approximately solved as aggregated LPs, and have error bounds developed by dominance, as in [3]. The advantage of these later bounds over the bounds in proposition 2 of [5] is that they require significantly less computation,

though they produce a looser bound. The notation of this paper follows that of [5] whenever possible. Only weighted column aggregated problems are considered, as the extension to row and column aggregated problems are straightforward.

II. The Model

The original LP is:

$$\begin{aligned} z^* &= \max cx \\ \text{subject to } Ax &\leq b \\ x &\geq 0 \end{aligned} \quad (2.1)$$

where $c = (c_j)$ is an n -vector, $b = (b_i)$ is an m -vector, $A = (a_{ij})$ is an $m \times n$ matrix, and $x = (x_j)$ is an n -vector of variables.

Let $\sigma = \{S_k : k = 1, \dots, K\}$ be an arbitrary partition of $\{1, \dots, n\}$, and $|S_k| = n_k$. Define A^k to be the submatrix of A consisting of those columns whose indices are in S_k . Define c^k and x^k similarly. Let g^k be a nonnegative n_k -vector whose components sum to unity, and define:

$$\bar{A}^k = A^k g^k, \quad \bar{c}_k = c^k g^k \quad k = 1, \dots, K$$

Let $\bar{A} = (\bar{A}^1, \dots, \bar{A}^K)$, $\bar{c} = (\bar{c}_1, \dots, \bar{c}_K)$ and X a K -vector of variables. Then the weighted column aggregate problem of (2.1) is:

$$\begin{aligned} \bar{z} &= \max \bar{c} X \\ \text{subject to } \bar{A} X &\leq b \\ X &\geq 0 \end{aligned} \quad (2.2)$$

Zipkin [5] shows that for any partition $\sigma' = \{S'_k; k = 1, \dots, K'\}$ of $\{1, \dots, n\}$ such that there exists known positive numbers $\{d_1, \dots, d_n\}$ and known nonnegative numbers $\{p_1, \dots, p_{K'}\}$ with:

$$\sum_{j \in S'_k} d_j x_j^* \leq p_k \quad k = 1, \dots, K' \quad (2.3)$$

then:

$$\bar{z} \leq z^* \leq \bar{z} + \sum_{k=1}^{K'} \left[\max_{j \in S'_k} \left\{ (c_j - \bar{u} A^j) / d_j \right\} \right] p_k$$

where $\bar{u}$ is the vector of optimal dual variables of (2.2).

Kallio assumes there exists two n -vectors, ℓ and p , $0 \leq \ell \leq u < \infty$ such that if the constraint

$$\ell \leq x \leq p$$

is added to (2.1), then the value of an optimal solution is unchanged. Let $\bar{z}$ be the value of a current solution, let $\bar{u}$ be the present dual vector, and define $\bar{c}$, $\bar{\delta}$, and $\bar{\mu}$ by:

$$\bar{c} = (\bar{c}_j), \quad \bar{c}_j = c_j - \bar{u} a_j; \quad \bar{\delta} = (\bar{\delta}_j), \quad \bar{\delta}_j = \max \{0, \bar{c}_j\}$$

$$\bar{\mu} = (\bar{\mu}_j), \quad -\bar{\mu}_j = \min \{0, \bar{c}_j\}$$

Then Kallio shows:

$$\bar{z} \leq z^* \leq \bar{u} b + \bar{\delta} p - \bar{\mu} \ell \quad (2.4)$$

Furthermore, the dual problem:

$$\begin{aligned}
 & \min ub + \delta p - \mu \ell \\
 & \text{subject to } uA + \delta - \mu \geq c \\
 & \delta, \mu \geq 0
 \end{aligned} \tag{2.5}$$

restricted to $\{u | u = g + \theta d, \theta \in \mathbb{R}\}$ can be solved by solving:

$$\begin{aligned}
 & \min K + \omega \theta + \delta p - \mu \ell \\
 & \text{subject to } h\theta + \delta - \mu \geq c^* \\
 & \delta, \mu \geq 0
 \end{aligned} \tag{2.6}$$

$$K \equiv gb, \omega \equiv db$$

$$h \equiv (h_j) \equiv dA, c^* = (c_j^*) \equiv c - gA$$

Kallio shows how the dual problem (2.6) can be solved by marginal analysis, and yields a tighter bound than does (2.4). In particular, convenient values of d and g are $g \equiv 0$ and $d = \bar{u}$. Then $h_j = c_j - \bar{c}_j$, and $c_j^* = c_j$.

For the aggregated problem (2.2), suppose $\bar{z}$ is given, and also known are the optimal dual variables $\bar{u}$. Also assume (2.3), where for convenience it is assumed that $d_j = 1$ for all j . Consider the restricted primal to (2.1):

$$\begin{aligned}
 & \text{maximize } cx \\
 & \text{s.t. } Ax \leq b
 \end{aligned} \tag{2.7}$$

$$\begin{aligned}
 & \sum_{j \in S_k} x_j \leq p_k \quad k = 1, \dots, K \\
 & x_j \geq 0
 \end{aligned}$$

and the equivalent restricted dual:

$$\begin{aligned} & \text{minimize } ub + \sum_{k=1}^K \delta_k p_k \\ & \text{s.t. } \sum_i a_{ij} u_i + \delta_k \geq c_j \quad j \in S_k; \\ & \quad \quad \quad j = 1, \dots, m \end{aligned} \tag{2.8}$$

$$u \geq 0$$

$$\delta \geq 0$$

Define $\bar{c}$ as before, but define $\bar{\delta} = \{\bar{\delta}_k\}$ by:

$$\bar{\delta}_k = \max_{j \in S_k} (\bar{c}_j)^+$$

By assumption (2.1) and (2.7) have the same optimal value z^* .

Lemma 2.1 $(\bar{u}, \bar{\delta})$ is a feasible solution to (2.8).

Proof. By definition $\bar{\delta}_k = \left(\max_{j \in S_k} \left(c_j - \sum_i a_{ij} \bar{u}_i \right)^+ \right) \geq \left(c_j - \sum_i a_{ij} \bar{u}_i \right)$

for any $j \in S_k$. Then each constraint in (2.8) satisfies:

$$\sum_i a_{ij} \bar{u}_i + \bar{\delta}_k \geq \sum_i a_{ij} \bar{u}_i + c_j - \sum_i a_{ij} \bar{u}_i^+ \geq c_j$$

since if $(c_j - \sum_i a_{ij} \bar{u}_i)$ is nonpositive, then $\sum_i a_{ij} \bar{u}_i \geq c_j$, so the constraint is feasible. If $(c_j - \sum_i a_{ij} \bar{u}_i)$ is positive, then the constraint is $c_j \geq c_j$, which again is feasible.

□

Lemma 2.1 leads to the extension of Kallio's theorem 1 for the aggregated LP. Consider (2.8) with u restricted to the set:

$$\{u \mid u = \theta \bar{u}, \theta \in \mathbb{R}\} \quad (2.9)$$

The new restricted dual is:

$$\begin{aligned} & \text{minimize } \bar{z}\theta + \sum_k \delta_k p_k \\ & \text{s.t. } \left(\sum_i a_{ij} \bar{u}_i \right) \theta + \delta_k \geq c_j \quad j \in S_k \quad (2.10) \\ & \quad \quad \quad j = 1, \dots, n \\ & \quad \quad \quad u \geq 0 \\ & \quad \quad \quad \delta_k \geq 0 \quad k = 1, \dots, K \end{aligned}$$

Let $z(\theta)$ be an optimal value of (2.10) for a given value of θ . Then an optimal solution to (2.8) with the added constraint (2.9) can be found by minimizing $z(\theta)$ with respect to θ , as in [2].

Theorem 2.1. $z(\theta)$ is a convex and piecewise linear function.
Let $z_-(\theta)$ be the left-hand derivative of $z(\theta)$ with respect to θ . Then
the possible discontinuity points of $z_-(\theta)$ where an optimum can occur
are at $\theta_1, \dots, \theta_n$ where:

$$\theta_j = \begin{cases} c_j / \sum_i a_{ij} \bar{u}_i & \sum_i a_{ij} \bar{u}_i \neq 0 \\ \infty & \sum_i a_{ij} \bar{u}_i = 0, \text{ for all } j. \end{cases}$$

Proof. For a fixed value of θ , (2.10) is decomposable into the following K subproblems:

$$\begin{aligned} & \text{minimize } \delta_k p_k \\ & \text{s.t. } \delta_j \geq c_j - \theta \left(\sum_i a_{ij} \bar{u}_i \right) \quad j \in S_k \end{aligned} \quad (2.11)$$

The solution of (2.11) is readily obtained as:

$$\max_{j \in S_k} \left(c_j - \theta \left(\sum_i a_{ij} \bar{u}_i \right) \right)^+ p_k \quad (2.12)$$

Possible points of discontinuity are at $c_j / \sum_i a_{ij} \bar{u}_i$ for all $j \in S_k$, and also at all values of θ such that

$$\left(c_j - \theta \left(\sum_i a_{ij} \bar{u}_i \right) \right) = \left(c_r - \theta \left(\sum_i a_{ir} \bar{u}_i \right) \right)$$

for $j, r \in S_k$. However, unless all such constraints in (2.11) are nonpositive, an optimum can only occur at the points $c_j / \left(\sum_i a_{ij} \bar{u}_i \right)$.

Equation (2.12) is clearly convex and piecewise linear in θ . Then:

$$z(\theta) = \bar{z}\theta + \sum_{k=1}^K \left[\max_{j \in S_k} \left(c_j - \theta \left(\sum_i a_{ij} \bar{u}_i \right) \right)^+ \right] p_k$$

which is convex and piecewise linear since it is the sum of such functions. Similarly, its points of discontinuity at an optimum can only be $\theta_1, \dots, \theta_n$.

□

Let $z(\theta^*)$ be the minimum value of $z(\theta)$, that is an optimal solution to (2.8) subject to (2.9).

$$\text{Let } \xi_a = \sum_{k=1}^{K'} \left[\max_{j \in S_k} \{c_j - \bar{u}A^j\}^+ \right] p_k$$

which is the error term in Zipkin's bound.

$$\text{Corollary 2.1} \quad \bar{z} \leq z^* \leq z(\theta^*) \leq \bar{z} + \xi_a$$

Proof. $z(\theta^*) \leq \bar{z} + \xi_a$ since $\bar{z} + \xi_a$ is equivalent to $z(1)$, and θ^* minimizes $z(\theta^*)$. By weak duality, a solution to (2.8) is greater than or equal to a solution to (2.7). Since (2.9) restricts (2.8), $z(\theta^*)$ is no less than an optimal value to (2.8), hence $z(\theta^*)$ is a legitimate upper bound.

□

Following and extending Kallio, the following method of marginal analysis yields an optimal value of θ . For any value of θ , define $J(\theta, k)$ as the j such that:

$$c_j(\theta, k) - \theta \sum_i a_{ij}(\theta, k) \bar{u}_i = \max_{j \in S_k} \left(c_j - \theta \sum_i a_{ij} \bar{u}_i \right)$$

and let $J(\theta) = \{j \mid j \in J(\theta, k), k = 1, \dots, K\}$.

$$\text{Then } z_-(\theta) = \bar{z} - \sum_{j \in I(\theta)} p_k \left(\sum_i a_{ij} \bar{u}_i \right)$$

where $I(\theta) = \left\{ j \mid j \in J(\theta); \theta_j \leq \theta \text{ and } \sum_i a_{ij} \bar{u}_i < 0 \text{ or } \theta_j > \theta \text{ and } \sum_i a_{ij} \bar{u}_i \geq 0 \right\}$.

The marginal analysis is as follows:

- 1) Choose any $\theta_i \in \{\theta_1, \dots, \theta_n\}$
- 2) Evaluate $z_-(\theta_i)$
- 3) If $z_-(\theta_i)$ equals zero or changes sign at θ_i , θ_i is optimal. Otherwise, if $z_-(\theta_i)$ is negative, increase to the next largest element in $\{\theta_1, \dots, \theta_n\}$, and if $z_-(\theta_i)$ is positive, decrease to the next smallest element in $\{\theta_1, \dots, \theta_n\}$.

At θ^* , the value of $z(\theta^*)$ can also be evaluated as:

$$z(\theta^*) = \bar{z}\theta + \sum_{j \in I(\theta)} \left(c_j - \theta \sum_i a_{ij} \bar{u}_i \right) p_k \quad (2.13)$$

The summation in (2.13) contains at most K terms.

Example 1. This example is from Zipkin [5]. The original problem is:

$$\begin{aligned} z^* = \max \quad & 2.5x_1 + 3x_2 + 4x_3 + 5x_4 \\ \text{subject to} \quad & 4x_1 + 5x_2 + 7x_3 + 10x_4 \leq 54 \\ & x_1 + 2x_2 + x_3 + 2x_4 \leq 10 \\ & x_1, x_2, x_3, x_4 \geq 0 \end{aligned}$$

An optimal solution is $x_1^* = 16/3$, $x_3^* = 14/3$, $x_2^* = x_4^* = 0$, $z^* = 32$.

Let $K = 2$, $s_1 = \{1, 2\}$, $s_2 = \{3, 4\}$, and the column weights in each partition be $(0.5, 0.5)$. Then $\bar{z} = 28^{5/6}$ and $\bar{u} = (2^{1/48}, 2^{5/48})$. Zipkin gives bounds for $p_1 = 10$, $p_2 = 8$:

$$28^{5/6} \leq z^* \leq 34^{11/24}$$

For finding the improved upper bound,

$$\theta_1 = 1.101 \quad \theta_2 = 0.4290; \quad \theta_3 = 1.116 \quad \theta_4 = 0.9231$$

$$\theta^* = \theta_1 = 1.101$$

and the improved bound is:

$$28\frac{5}{6} \leq z^* \leq 32.1855$$

which is an extremely tight upper bound on the true optimal value $z^* = 32$.

Example 2. Again from [5], this is the same problem as example 1, but the aggregation weights are changed to (0.75, 0.25). Then $\bar{z} = 30\frac{2}{7}$ and $\bar{u} = (6\frac{5}{140}, 7\frac{3}{140})$. Zipkin's bounds are

$$30\frac{2}{7} \leq z^* \leq 33\frac{2}{7}$$

For the improved bound:

$$\theta_1 = 1.051 \quad \theta_2 = 0.8917; \quad \theta_3 = 1.0606 \quad \theta_4 = 0.8794$$

$$\theta^* = \theta_1 = 1.051$$

and the improved bound is:

$$30\frac{2}{7} \leq z^* \leq 32.1231$$

which again is an extremely tight upper bound.

III. Application to MDP's

A discounted MDP defined on the integers $X = \{1, \dots, n\}$ is controlled over an infinite planning horizon. For each state $x \in X$, feasible decisions $Y(x)$ are available. If $y \in Y(x)$ is the decision chosen, then an immediate reward $G(x, y)$ is received, and a transition is made to state $j \in X$ with probability P_{xj}^y . The one-period rewards are discounted by a factor α , $0 \leq \alpha < 1$, and the object is to maximize the total expected reward over an infinite horizon. It is well known that this problem can be solved by the following LP (d'Epenoux [1]):

$$\begin{aligned}
 & \text{maximize} \quad \sum_{x=1}^n G(x, y) u_x^y \\
 & \text{s.t.} \quad \sum_{x=1}^n \sum_{y \in Y(x)} \left(\delta_{xj} - \alpha P_{xj}^y \right) u_x^y = 1 \quad j = 1, \dots, n \\
 & \quad \quad \quad u_x^y \geq 0 \quad x \in X \\
 & \quad \quad \quad y \in Y(x)
 \end{aligned} \tag{3.1}$$

If it is assumed that $G(x, y)$ is uniformly (finitely) bounded from below, then the equalities in (3.1) can be transformed into inequalities.

MDPs that arise from real problems can be so large that both (3.1) and any of the bounds cited previously for an aggregated version of (3.1) are computationally infeasible. In [3], bounds are developed that are looser than ξ_a but require less computation. (Again, only column aggregation is considered, as improved lower bounds can be obtained similarly; see [4].) For each S_k , let $(x, y) \in S_k$ denote that the column associated with choosing action y from state x is in the partition S_k . Define:

$$G^k(x, y) \geq \max_{(x, y) \in S_k} G(x, y) \quad k = 1, \dots, K$$

$$P_{xj}^k \geq \max_{(x, y) \in S_k} P_{xj}^y \quad \text{for all } j \in X$$

and for each k , let $H_k \subset X$ be the set of x such that at least one $(x, y) \in S_k$. Let $\bar{f}$ be the optimal dual variables to an aggregated version of (3.1), then define f_k^* as:

$$f_k^* = \min_{x \in H_k} \bar{f}_x \quad k = 1, \dots, K$$

Then the following bound on an aggregated LP can be derived [3]:

$$\bar{z} \leq z^* \leq \sum_{k=1}^K \left[\left(G^k(x, y) + \alpha \sum P_{xj}^k \bar{f}_j - f_k^* \right)^+ \right] p_k \quad (3.2)$$

The advantage of (3.2) is that only K terms are evaluated, that is only as many terms as are in the aggregated version of (3.1).

For each partition S_k , $k = 1, \dots, K$, define two terms:

$$h_k^+ \geq \max_{(x, y) \in S_k} \left\{ \bar{f}_x - \alpha \sum P_{xj}^y \bar{f}_j \right\}$$

$$h_k^- \leq \min_{(x, y) \in S_k} \left\{ \bar{f}_x - \alpha \sum P_{xj}^y \bar{f}_j \right\}$$

and define θ_k^+ , θ_k^- as:

$$\theta_k^+ = G^k(x, y) / h_k^+$$

$$\theta_k^- = G^k(x, y) / h_k^-$$

Define $K(\theta, k)$ as:

$$K(\theta, k) = \begin{cases} \theta_k^+ & \text{if } G^k(x, y) - \theta h_k^+ \geq G^k(x, y) - \theta h_k^- \\ \theta_k^- & \text{otherwise} \end{cases}$$

and define the set $K(\theta)$ as

$$K(\theta) = \left\{ k \mid K(\theta, k) > \theta \text{ and } K(\theta, k) = \theta_k^- \text{ or } K(\theta, k) \leq \theta \text{ and } K(\theta, k) = \theta_k^+ \right\}$$

Let the function $v(\theta)$ be defined as:

$$v(\theta) = \bar{z}\theta + \sum_{k \in K(\theta)} (G^k(x, y) - \theta w_k) p_k$$

where

$$w_k = \begin{cases} h_k^+ & \text{if } K(\theta, k) = \theta_k^+ \\ h_k^- & \text{otherwise} \end{cases}$$

and minimize $v(\theta)$ with respect to θ using the following marginal analysis:

1) Choose: $\theta \in \left\{ \theta_1^+, \theta_1^-, \dots, \theta_k^+, \theta_k^- \right\}$

2) Evaluate: $v_-(\theta) = \bar{z} - \sum_{k \in K(\theta)} w_k p_k$

3) If $v_-(\theta)$ equals zero or changes sign at θ , then set

$\theta^+ = \theta$ and go to 4). Else, if $v_-(\theta)$ is negative, increase

θ to the value of the next largest element of

$\{\theta_1^+, \theta_1^-, \dots, \theta_k^+, \theta_k^-\}$. If $v_-(\theta)$ is positive, decrease

to θ to the value if the next smallest value of

$$\{\theta_1^+, \theta_1^-, \dots, \theta_k^+, \theta_k^-\}.$$

4) Evaluate $v(\theta)$ at θ^* .

Let θ^1 be an optimal θ found by this procedure, and θ^2 an optimal θ found by the procedure of section 2.

Theorem 3.1 $\bar{z} \leq z^* \leq z(\theta^2) \leq v(\theta^1) \leq$ upper bound in (3.2).

Proof: From (2.11), the contribution of any partition S_k to $z(\theta)$ for fixed θ is:

$$\begin{aligned} & \max_{(x, y) \in S_k} \left(G(x, y) - \theta(\bar{f}_x - \alpha \sum_j p_{xj}^y \bar{f}_j) \right)^+ p_k \\ & \leq \max_{(x, y) \in S_k} \left(G^k(x, y) - \theta(\bar{f}_x - \alpha \sum_j p_{xj}^y \bar{f}_j) \right)^+ p_k \end{aligned}$$

For $\theta \geq 0$:

$$\max_{(x, y) \in S_k} \left(G^k(x, y) - \theta(\bar{f}_x - \alpha \sum_j p_{xj}^y \bar{f}_j) \right)^+ \leq \left(G^k(x, y) - \theta h_k^- \right)^+ \quad (3.3a)$$

For $\theta < 0$:

$$\max_{(x, y) \in S_k} \left(G^k(x, y) - \theta(\bar{f}_x - \alpha \sum_j p_{xj}^y \bar{f}_j) \right)^+ \leq \left(G^k(x, y) - \theta h_k^+ \right)^+ \quad (3.3b)$$

Equation (3.3a) and (3.3b) imply that the contribution of partition S_k to $v(\theta)$ is greater than or equal to the contribution of partition S_k to $z(\theta)$. This implies at an optimum:

$$z(\theta^2) \leq v(\theta^1)$$

The rest of the theorem follows from theorem 2.1, and the fact that the upper bound in (3.2) is exactly $v(1)$.

□

Theorem 3.1 allows an improved bound to be calculated in much less computation than is needed for one simplex iteration on a problem with $2K$ columns.

Example 3. Mathews [6] gives the following equation for the return of salmon in the Naknek river:

$$x_{t+1} = 6.727 e^d y_t \exp \{-0.859 y_t\} \quad (3.4)$$

where d is distributed as $N(0, 0.1444)$. Equation (3.4) is discretized on the set:

$$X = \{0, 0.125, 0.25, 0.375, 0.5, 0.625, 0.75, 0.875, 1, 1.125, 1.25, 1.375, 1.5, 1.625, 1.75, 1.875, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9\}$$

where the units are 10^6 fish, and the decision set is:

$$Y(x) = \{y : 0 \leq y \leq x, x, y \in X\}.$$

A forthcoming paper will discuss in greater detail the discretization procedure and policy implications.

The one-period reward is $(x - y)$, and the discount factor used is $\alpha = 0.97$. The true optimal value is $z^* = 1918.1672$, by following a base stock policy given by:

$$y = \min\{x, 0.75\}.$$

The partitions, aggregating weights, and p_k , P^k , and G^k are given in Table 3.1. The bounds using ξ_a are:

$$624.2476 \leq z^* \leq 14,849.0491$$

The improved bounds using theorem 2.1 are:

$$624.2476 \leq z^* \leq 9,051.6241$$

which occurs at $\theta^* = (-0.027)$. This comes from partition 2, from the column associated with $u_{0.75}^{0.25}$.

The solution to the aggregated MDP gives a randomized policy for all states, weighted between $y = \{0, 0.125, 0.25, 0.375, 0.5\}$, which is not a desirable solution. Three observations arise from these results:

- 1) The improved upper bound gives a better idea of the true optimal value.
- 2) The unimproved upper bound gives a better feel of how "good" the present partitioning and aggregation is--that is the larger spread is more indicative that implementing the disaggregated "optimal" policy is probably undesirable.
- 3) The problem is highly deterministic. The root of $\frac{d}{dx}(\alpha 6.727 y \exp(-0.859 y) - y) = 0$ for $\alpha = 0.97$ is 0.774. Rounded down to the nearest grid point yields the proper optimal policy.

For this problem, the bounds by dominance are:

$$624.2476 \leq z^* \leq 347,663.366 \quad (3.5)$$

which are not very good, though simple to calculate.

A simple improved bound by dominance can be found at $\theta = 0$, though this is not the best improvement. In this case, the upper bound is:

$$\sum_{k=1}^K [G^k(x, y)]^+ p_k$$

which gives bounds of

$$624.2476 \leq z^* \leq 9,147.0000$$

This is a dramatic improvement over (3.5), and almost as good as the best upper bound. For very large MDP's, bounds by dominance may be the only ones available, and the improvement afforded by theorem 3.1 and the tightness of the bounds are encouraging.

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